How to produce protons for the LHC? (or electrons for the ILC)

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Lectures overview

I. How to produce protons for the LHC?

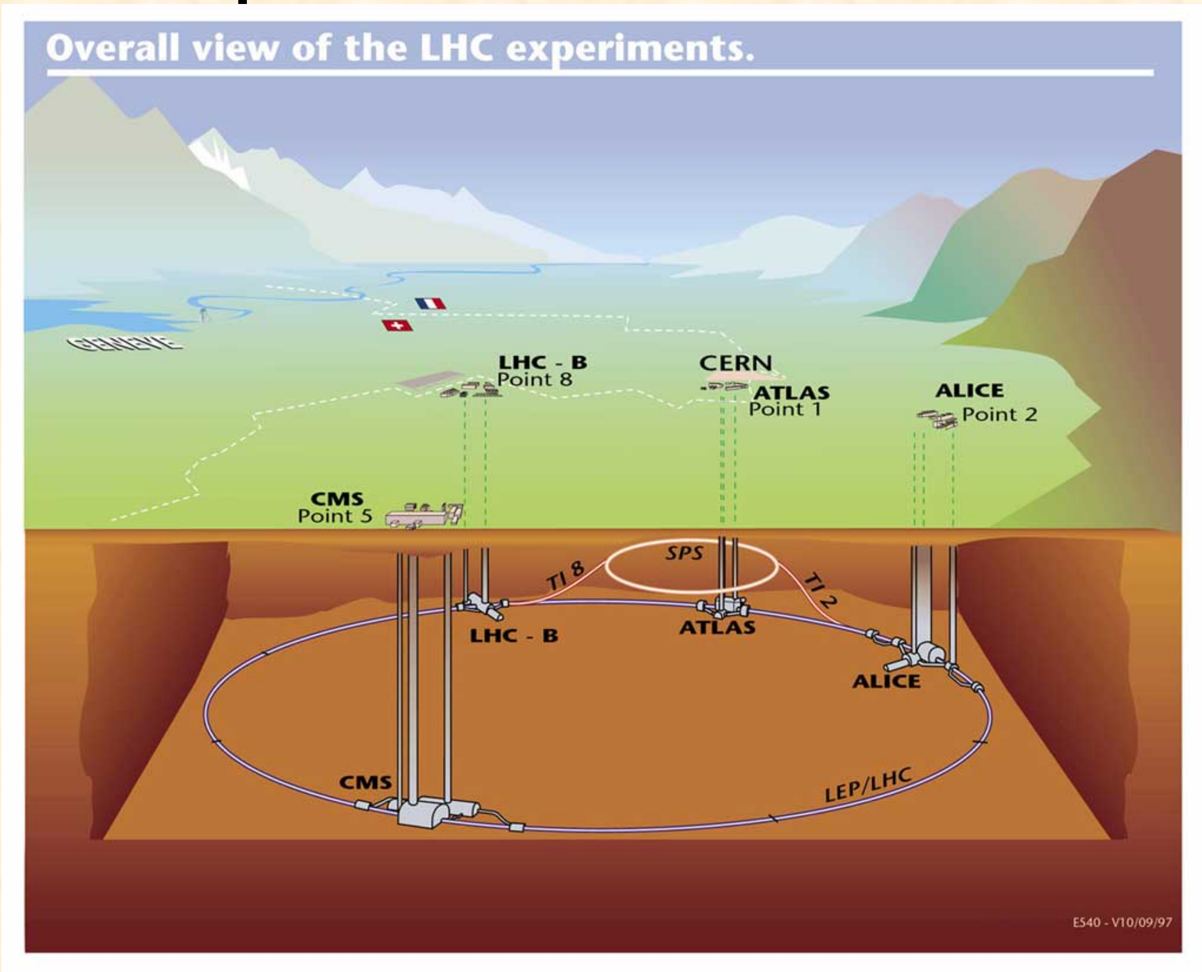
II. How to get protons in the LHC?

III. How to "see" protons in the LHC?

Who am I?

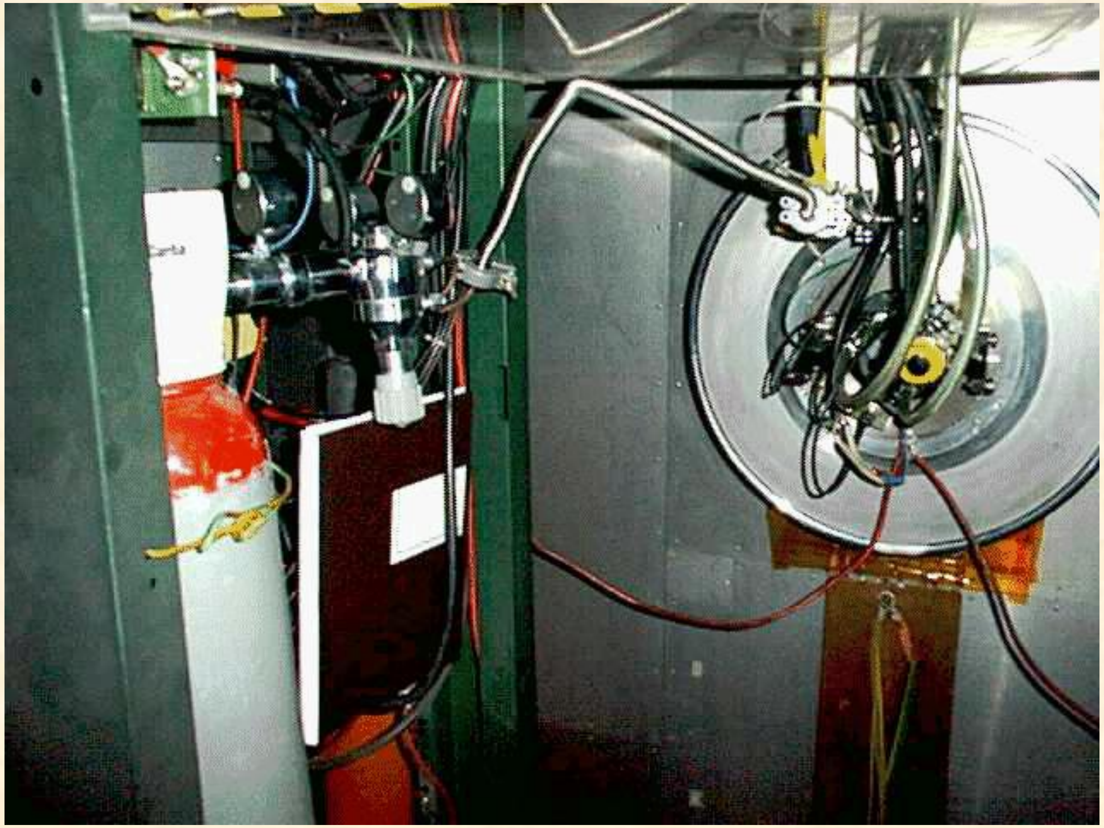
- Permanent researcher at LAL in Orsay, head of the diagnostics group in the accelerator department.
- Researching mostly on new particle accelerators:
  - How to measure some special radiation emitted by electrons *(more in this lecture)*
  - How to measure the “temperature” of electron beams *(more in this lecture)*
  - How to build new accelerators as source of X-rays and gamma rays *(this evening’s lecture)*
  - How to make accelerators much smaller *(this evening’s lecture)*
- In the past I also studied whether the electron and the neutrino have a substructure or not (using H1 data at HERA).

The LHC experiments need protons to take data



- These protons are provided by the LHC and the LHC accelerators complex.

Where do the Higgs bosons come from?



- So far all the Higgs bosons observed on earth came from the bottle above.
- At the LHC the protons (and then the Higgs) are produced by ionizing hydrogen.

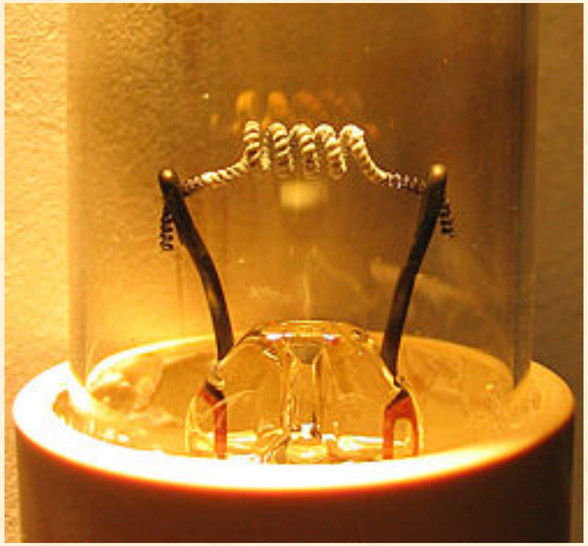
PARTICLE SOURCES

Electron sources: Thermionic effect

- The thermionic effect as at the heart of particle production in many accelerators.
  - Remember the Maxwell-Boltzmann energy distribution:

$$f = e^{\frac{-E}{k_B T}}$$

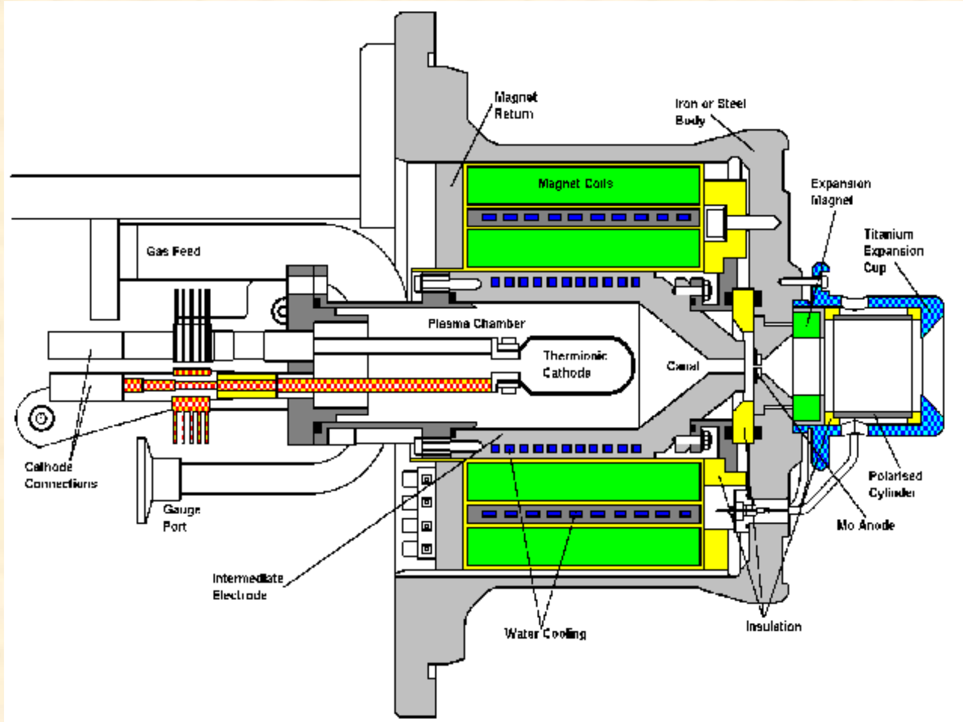
  - Electrons (fermions) obey a similar law.
  - When a metal is heated more electrons can populate high energy levels.
  - Above a certain threshold they electrons can break their bound and be emitted: This is thermionic emission.
  - Thermionic emission is used both in electron sources and in proton sources.



(image source: wikipedia)

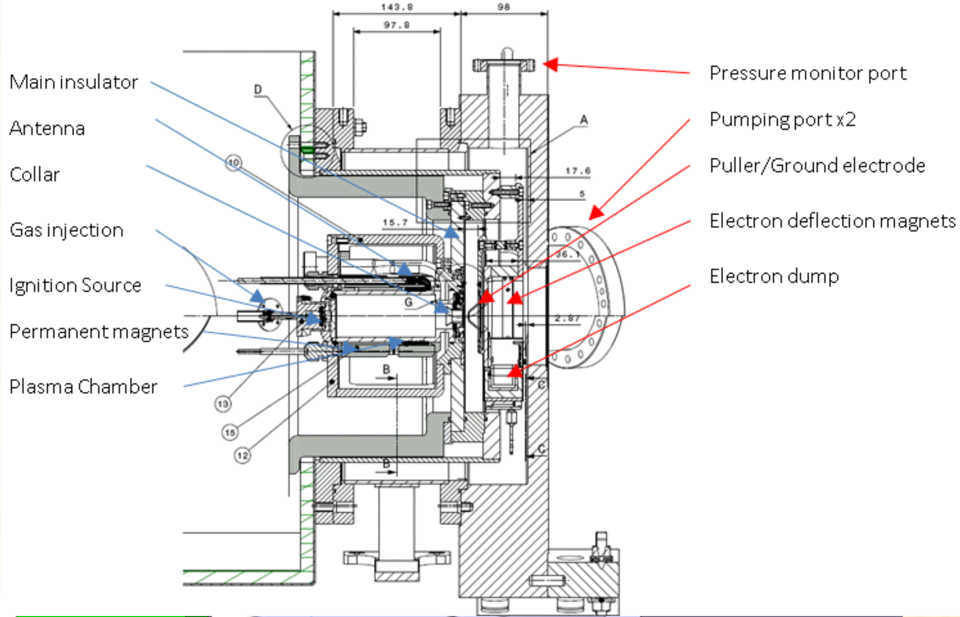
Proton source: the duoplasmotron

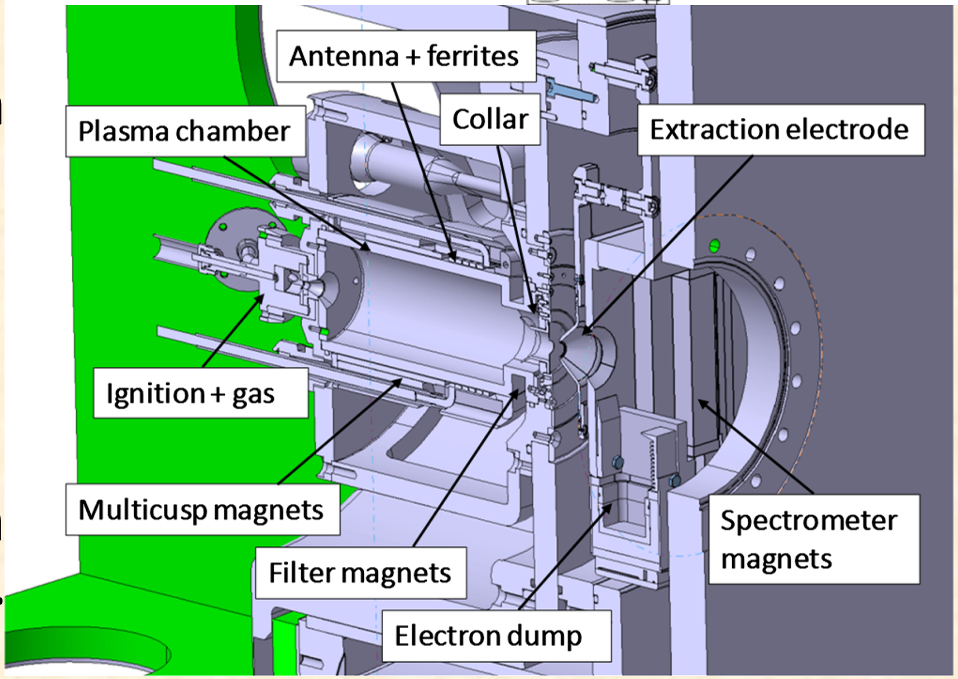
- At CERN the protons are produced in a duoplasmotron source.
- Hydrogen is injected in a plasma chamber at a high electric potential (100kV)
- Inside the plasma chamber a cathode emits electrons.
- These electrons hit the gas atoms and ionise them into protons.
- The protons are attracted toward lower potential areas and are ejected from the source.
- Magnets are used to minimise transverse momentum of the particles and focus them at the exit.



H- RF source

- In a Radiofrequency ion source an RF field is used to break the gas (hydrogen) into a plasma.
- This RF field is brought in the plasma chamber by an antenna.
- An intense electric field is used to separate the positive ions from the negative ions.
- The negative ions are then extracted and accelerated.



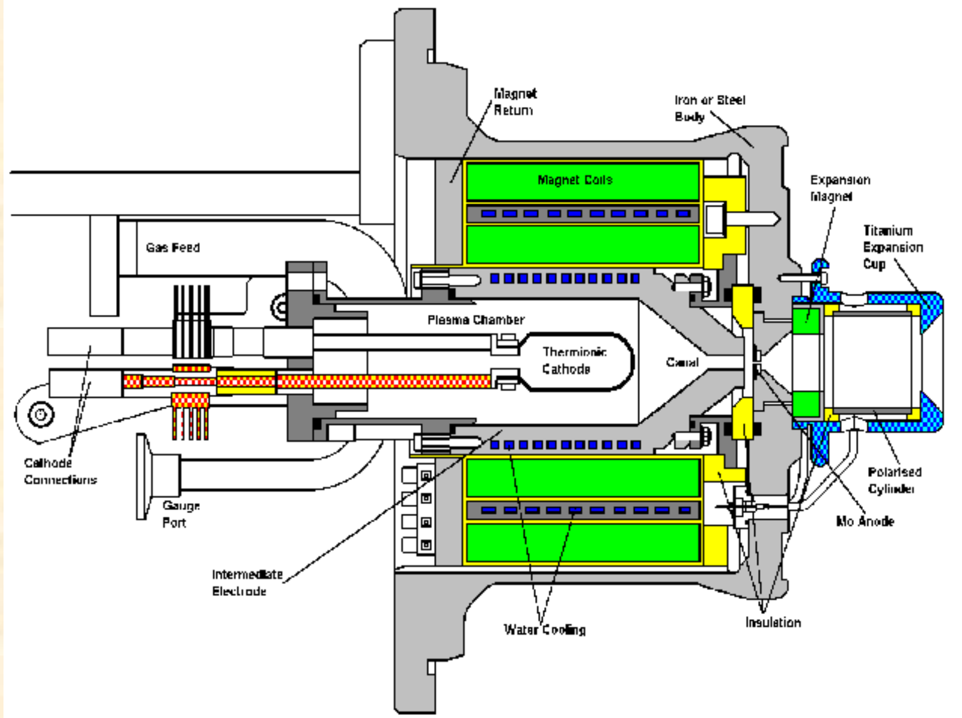


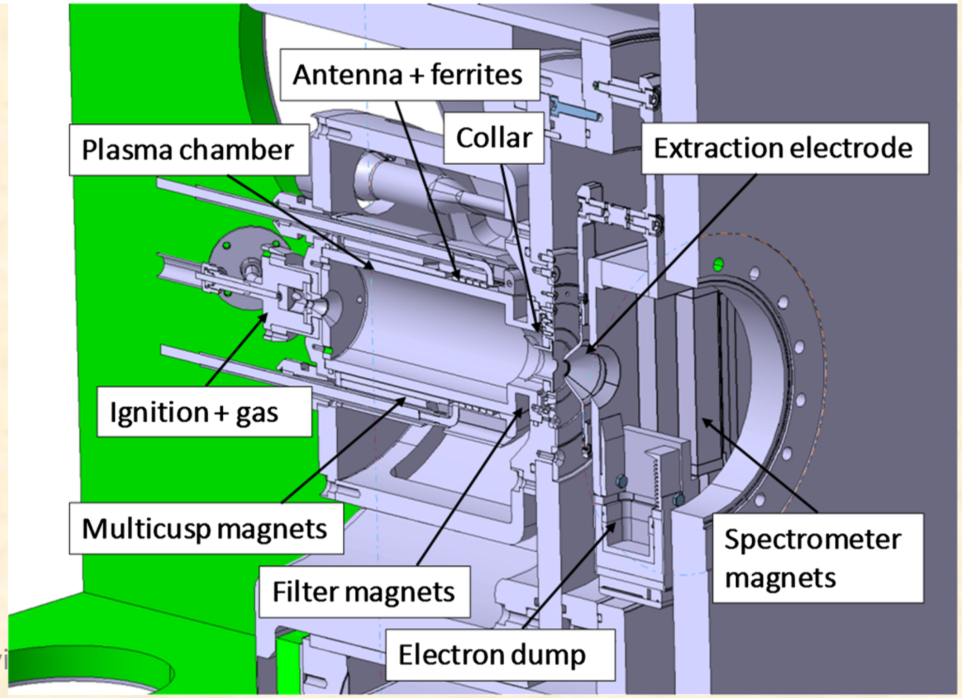
http://linac4ionsource.web.cern.ch/

Courtesy Richard Scrivens, CERN

Quizz

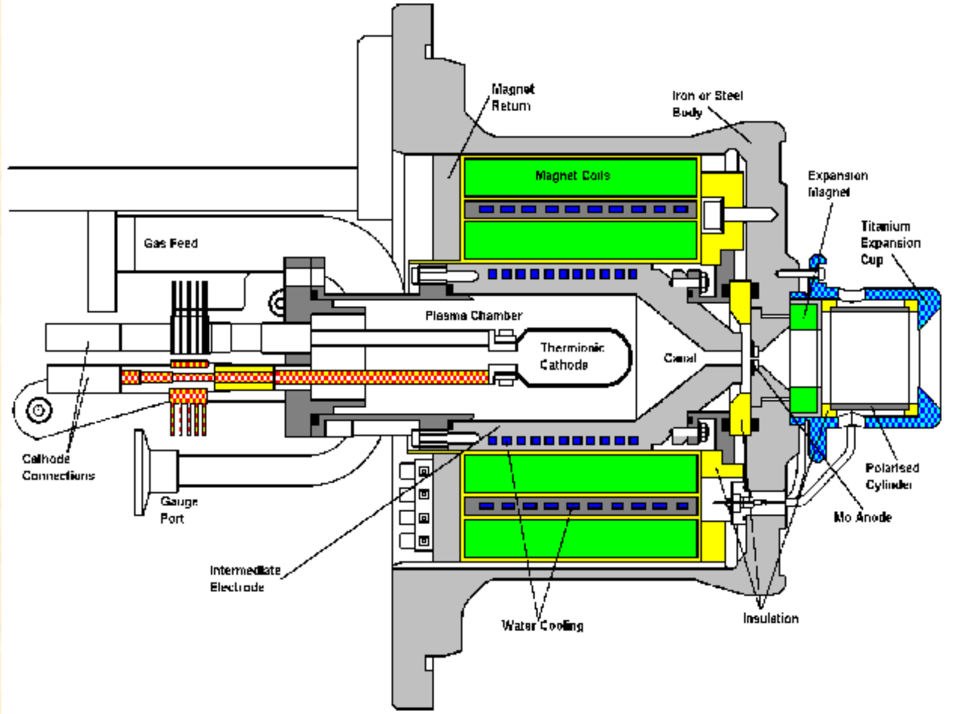
1) We have seen that in a duoplasmotron there is a thermionic electron source. Does that mean that this source produces both protons and electrons? Why?
2) Same question for the H- RF source.

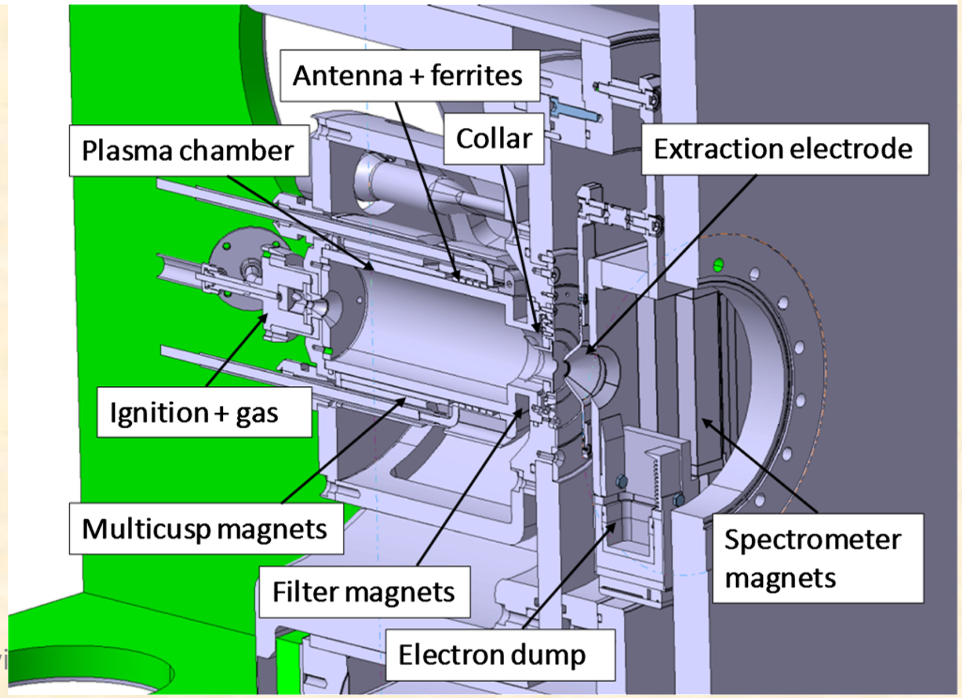




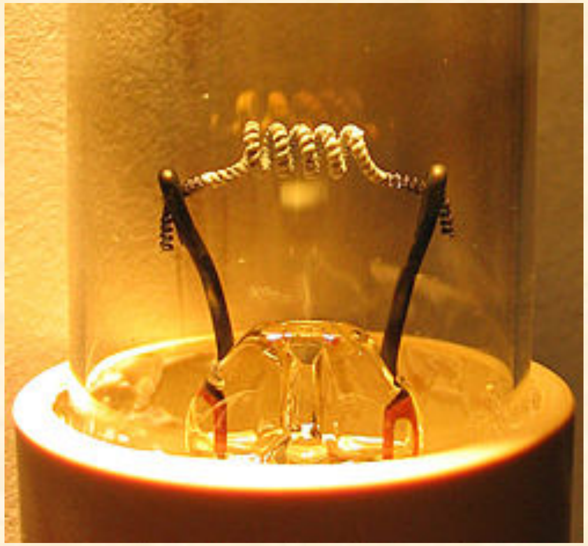
Answer

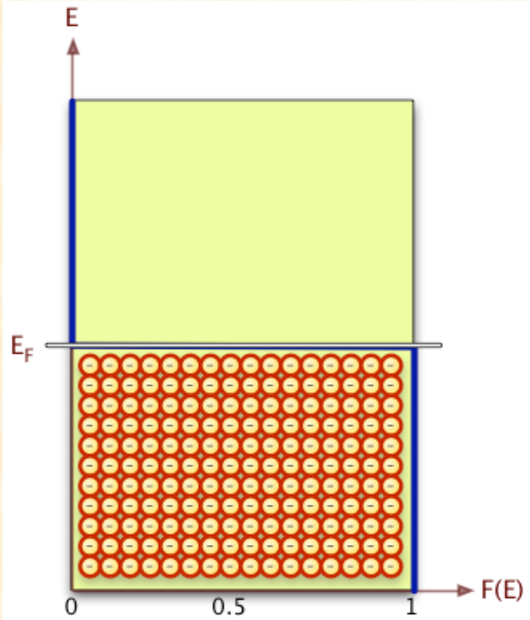
1) In the duoplasmotron the electric field separates the electrons from the proton as they have opposite charge. So only p+ are extracted.
2) This is not the case in a H- source where the electrons and the ions have the same charge. They must be separated by a magnet at the source exit. This must done carefully to limit heating of critical components.

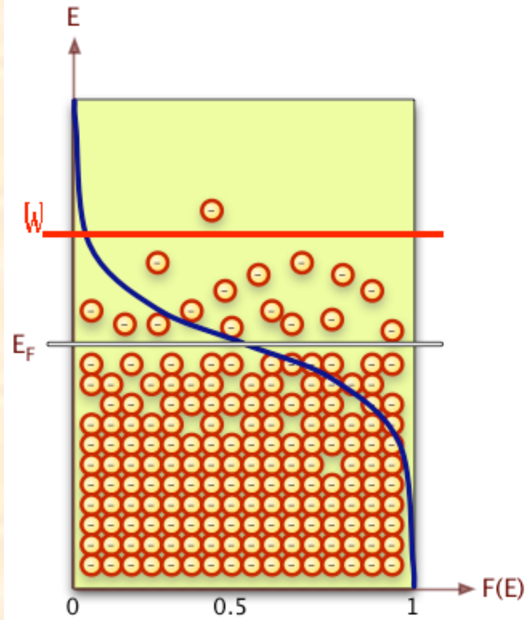




Electrons source: thermionic effect





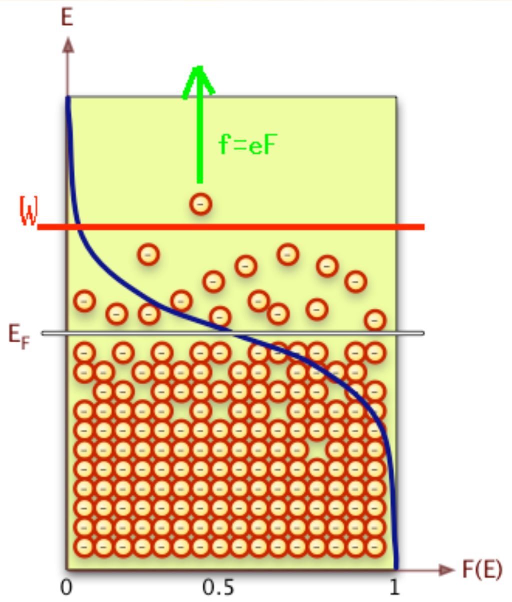


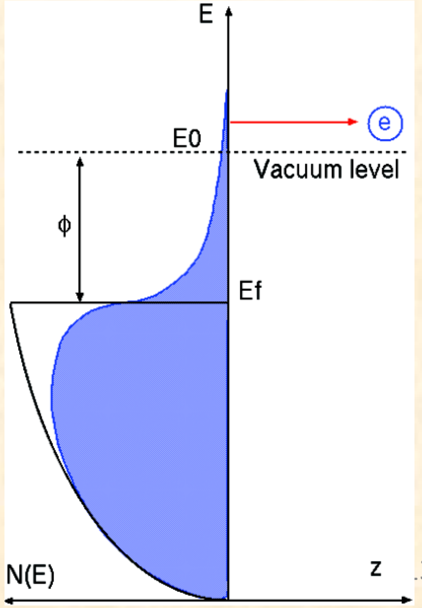
(image source: http://cnx.org/content/m13458/latest/

- We have already seen that electrons can be produced by thermionic effect.
- At low temperature all electrons are in the lowest possible energy level, below the Fermi level.
- As the temperature increase some electrons will go above the Fermi level.
- But only those with an energy greater than the "work function" are "free".

Electrons extraction

- Once the electrons are free they may fall back on the cathode.
- To avoid this an electric field needs to be applied.
- If a negative potential is applied to the cathode the electrons will be attracted away from the cathode after being emitted.
- The potential the electrons must overcome to escape is called the "work function".

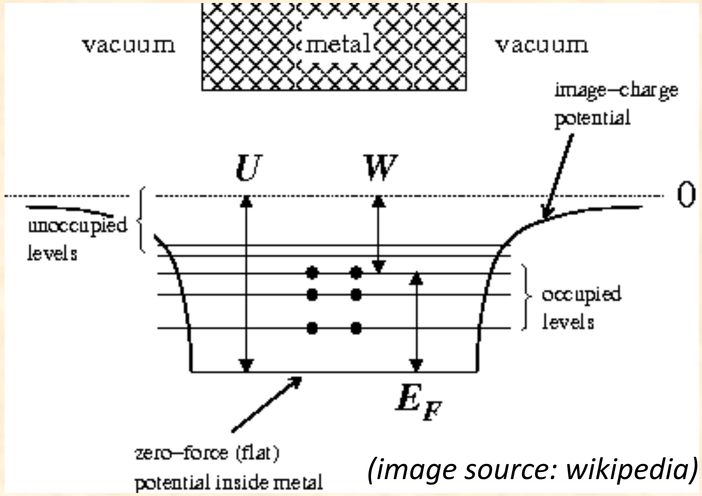




(image source: Masao Kuriki, ILC school)

Work function

- To escape from the metal the electrons must reach an energy greater than the edge of the potential well.
- The energy that must be gained above the Fermi energy is called the "work function" of the metal.
- The work function is a property specific to a given metal. It can be affected by many parameters (eg: doping, crystalline state, surface roughness,...)



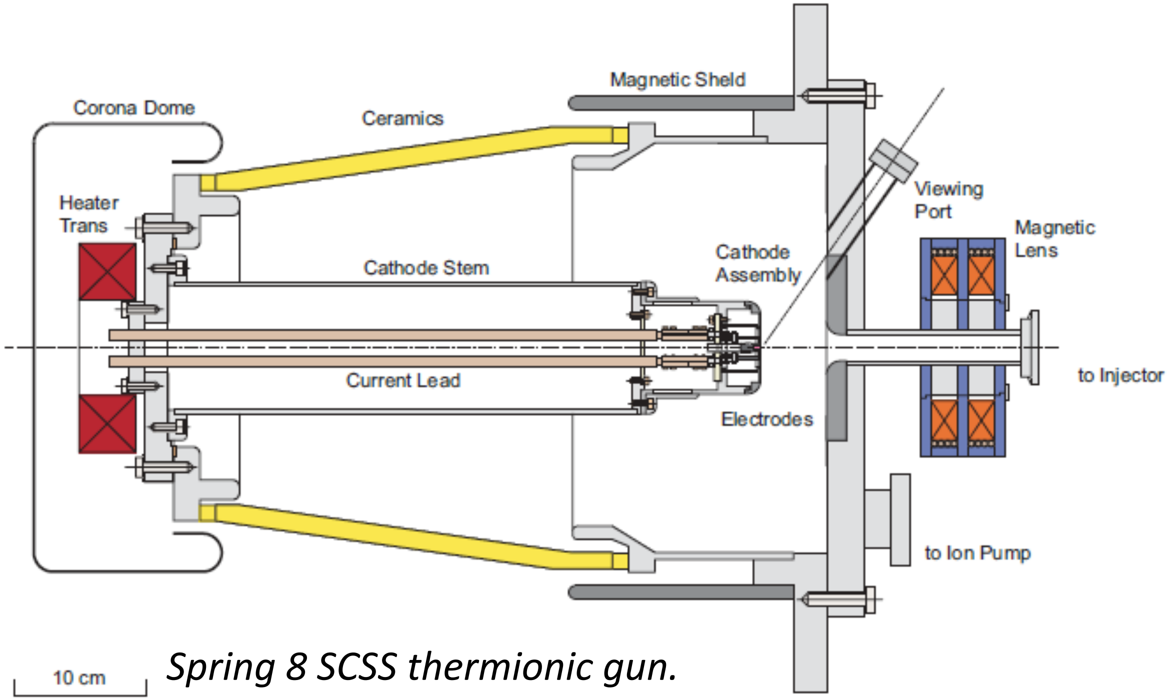
(image source: wikipedia)

- Example values:
  Fe: 4.7 eV ; Cu: ~5eV; Al: ~4.1 eV; **Cs: ~2 eV**

Example of thermionic gun

SCSS

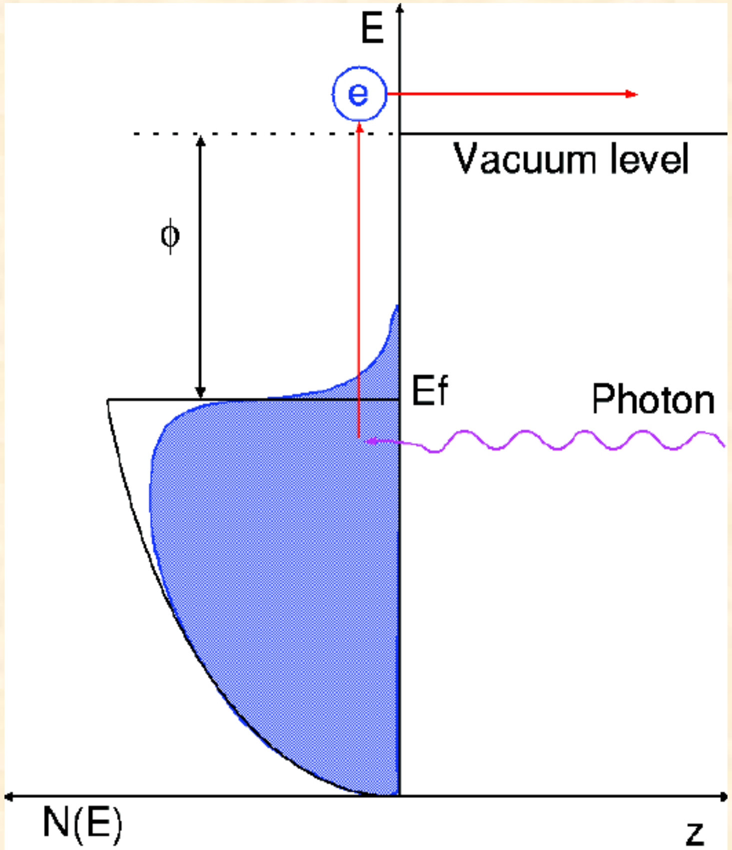
500kV Electron Gun



Spring 8 SCSS thermionic gun.
(images source: T. Shintake, Spring-8)

Photo-electric emission

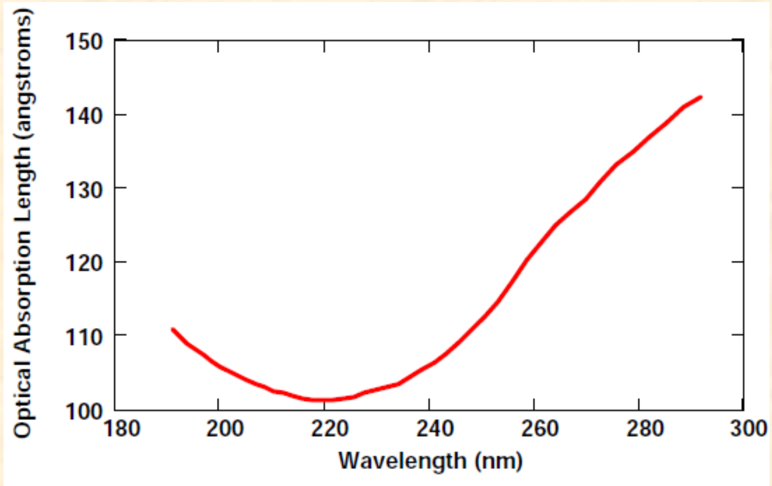
- A photon incident on a material will transfer its energy to an electron present in the metal.
- If the energy of this electron becomes bigger than the work function of the material, the electron can be emitted.
- This is called photo-electric emission.



(image source: Masao Kuriki, ILC school)

Photo-electric emission (2)

- A UV photon at 200nm carries an energy of about 6 eV, this is enough to “jump” over the work function of most metals.
- As seen in electromagnetism, electromagnetic waves (photons) can penetrate inside a metal over a short depth.
- The photo-electric emission may thus take place away from the surface.

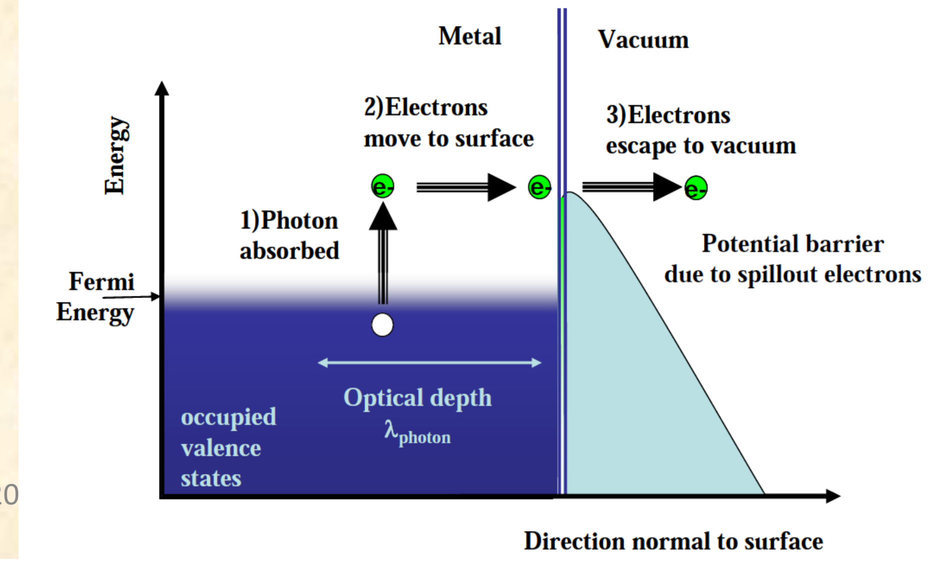


(image source: Dowell et al., Photoinjectors lectures)

The 3 steps of photo-electric emission

Photo-electric emission takes place in 3 steps:

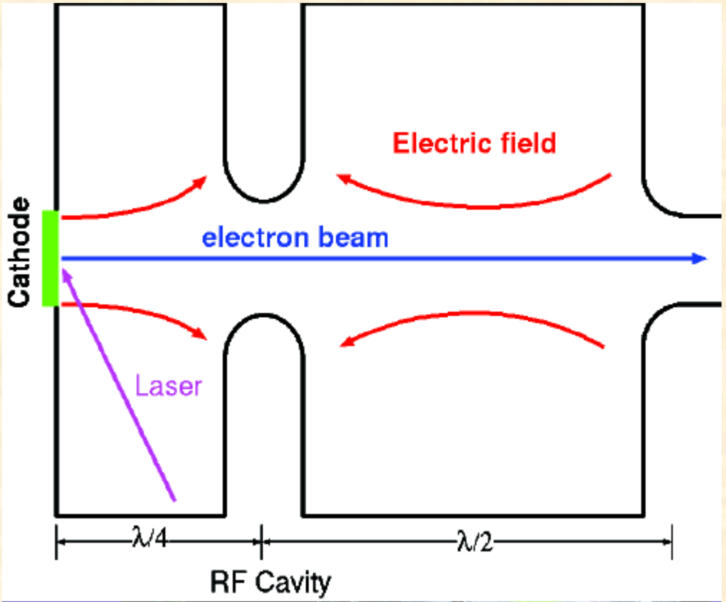
1) Absorption of a photon by an electron inside the metal. The energy transferred is proportional to the photon energy.
2) Transport of the photon to the physical surface of the metal. The electron may loose energy by scattering during this process.
3) Electron emission (if the remaining energy is above the work function; including Schottky effect)



The efficiency of this process is called "quantum efficiency".

RF Gun

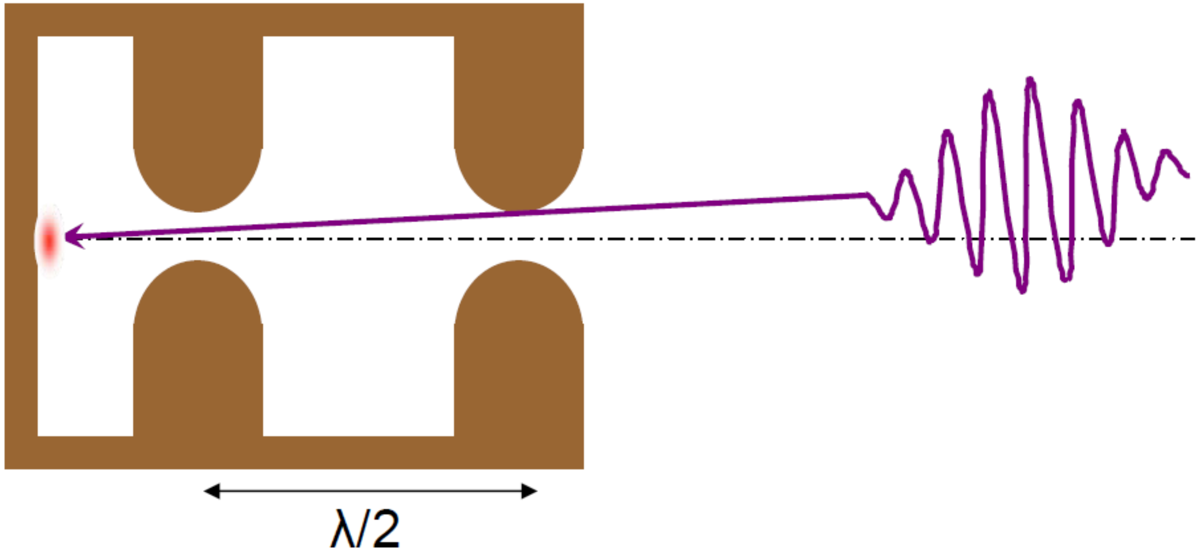
- The high voltage of a DC gun can be replaced by a RF cavity.
- This can provide much higher accelerating gradients and hence limit the space charge.
- RF guns are often coupled with a photo-cathode.
- RF gun can generate shorter bunches (using short laser pulses).



(images source:Masao Kuriki, ILC school)

Principle of a RF Photo-gun

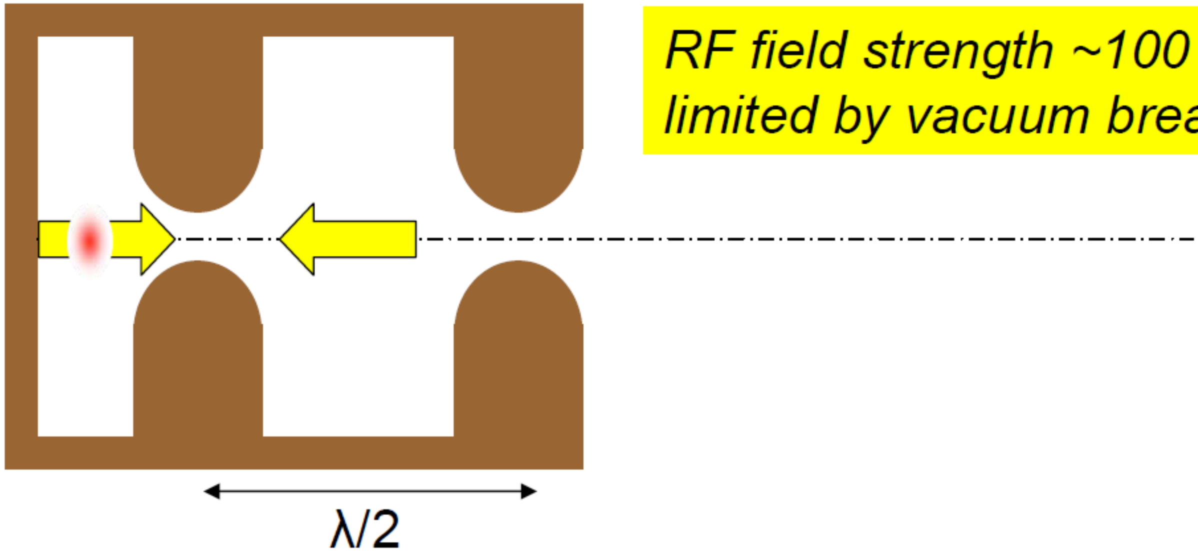
Pulsed laser photoemission...



Courtesy Jom Luiten, TUV Eindhoven

Principle of a RF Photo-gun

...and RF acceleration.



RF field strength ~100 MV/m, limited by vacuum breakdown

Courtesy Jom Luiten, TUV Eindhoven

Principle of a RF Photo-gun

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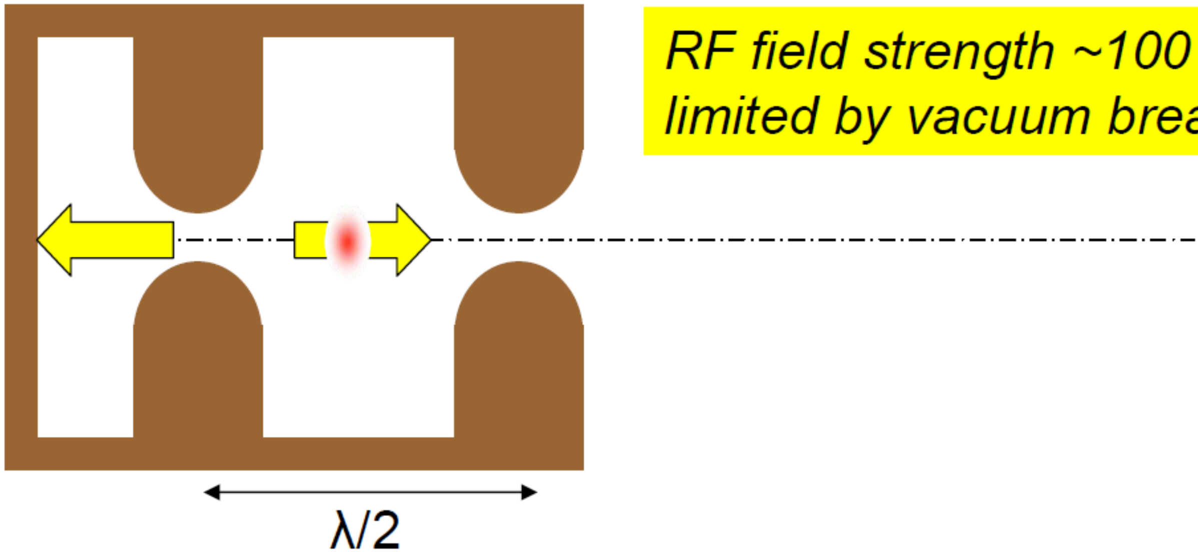

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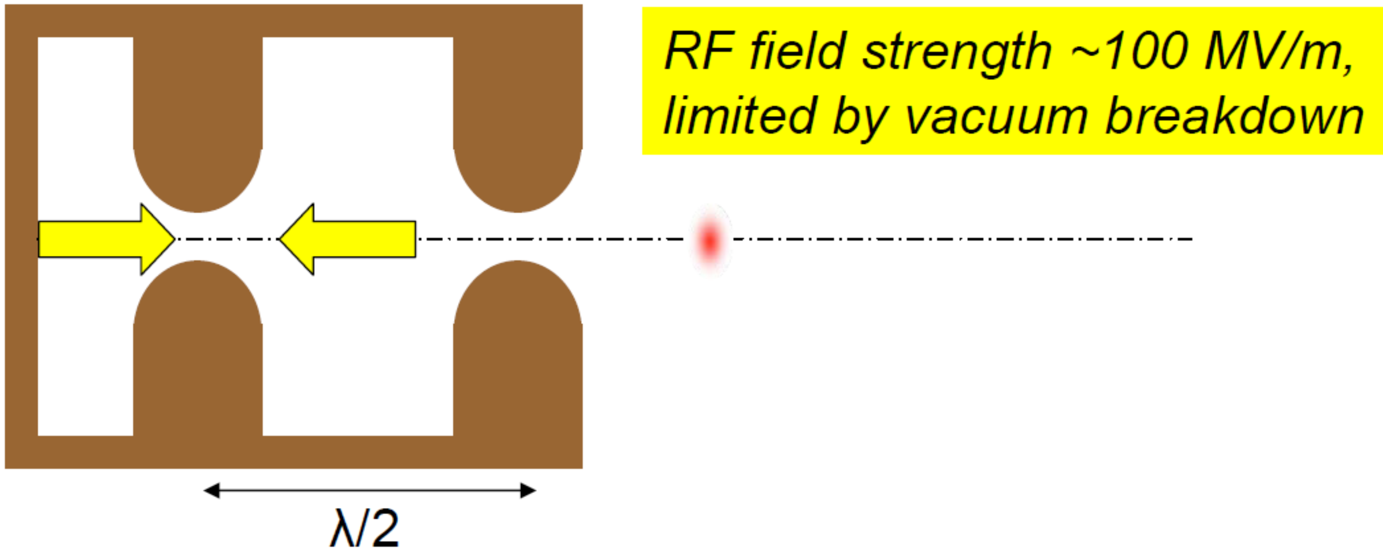
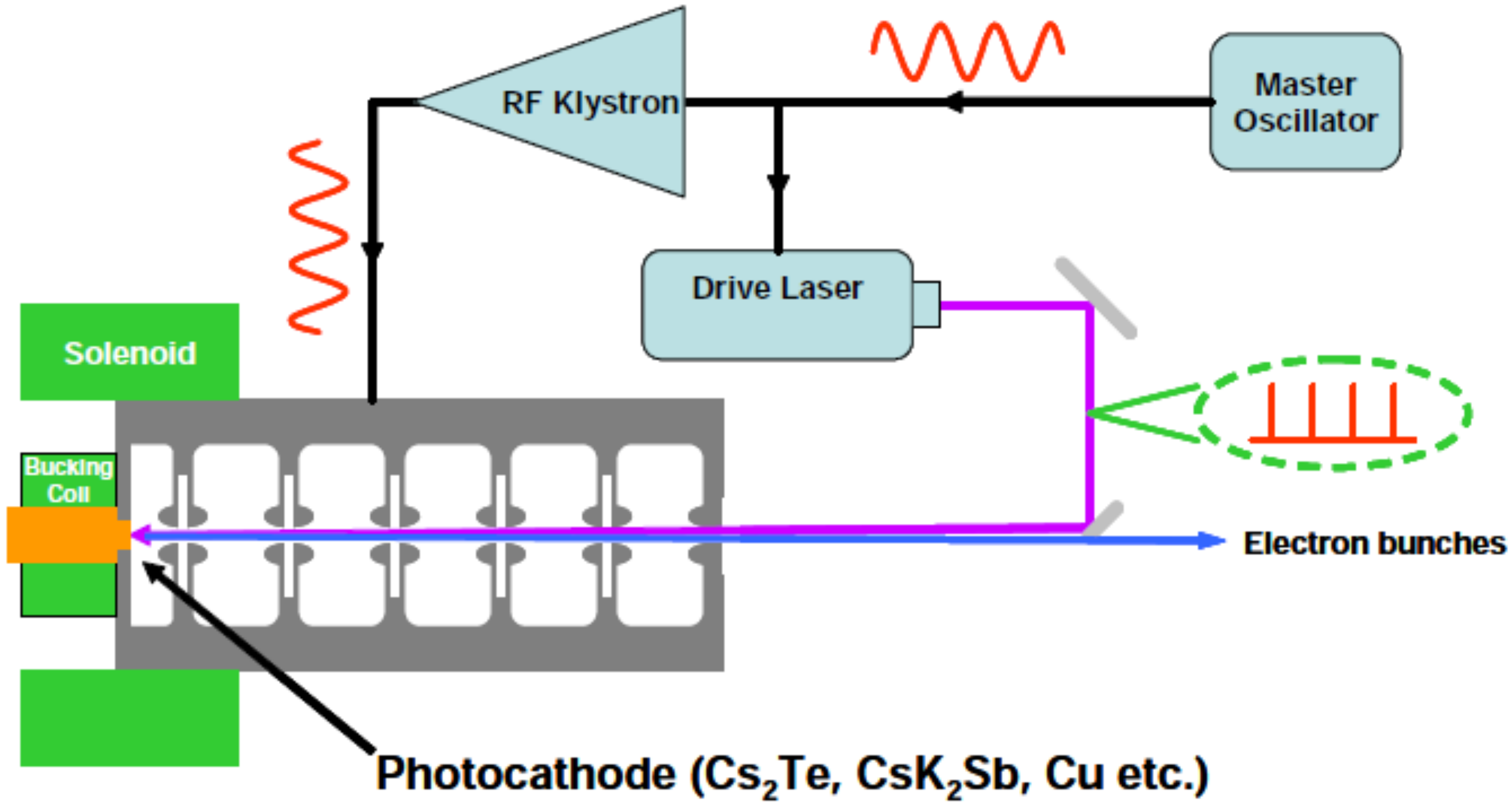


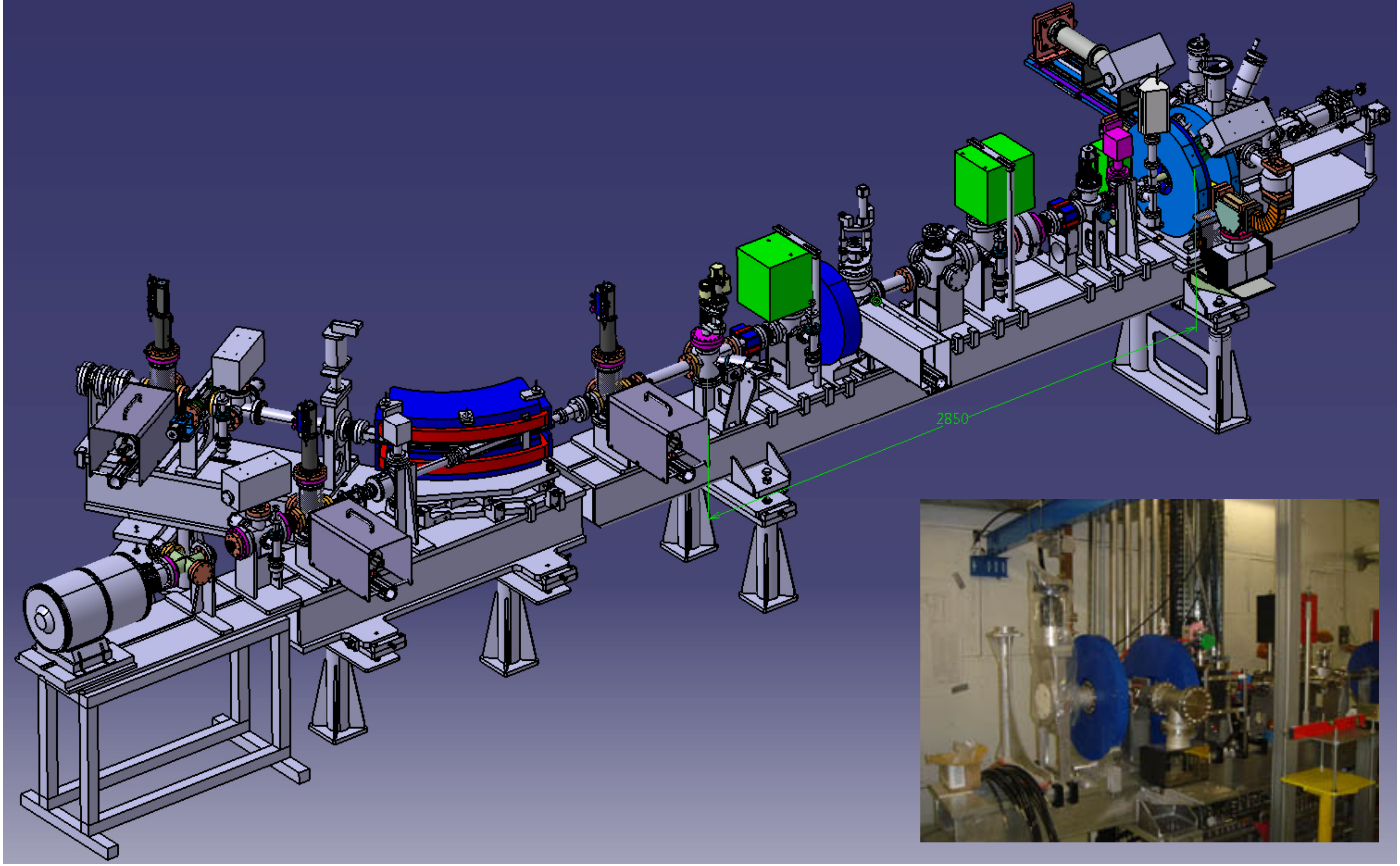
Courtesy Jom Luiten, TUV Eindhoven

RF photocathode gun



Slide compliments of P. O'Shea, UMd

PHIL: the LAL Photoinjector



Quizz

1) Which of these materials would give the highest thermionic emission current (at the same temperature)?
   (a) Iron (Fe); W=4.7 eV
   (b) Gadolinium (Gd); W=2.90 eV
   (c) Cobalt (Co); W=5 eV
2) Which laser would give the best quantum efficiency on a Copper-based photo-cathode (W=5 eV)
   (a) A 5GW CO2 laser (wavelength=10 micrometers)
   (b) A 10 kW frequency doubled Nd:YAG laser (wavelength=532nm)
   (c)A 3MW frequency quadrupled Ti-Sapphire laser (wavelength=200nm)

Answer 1: (b)

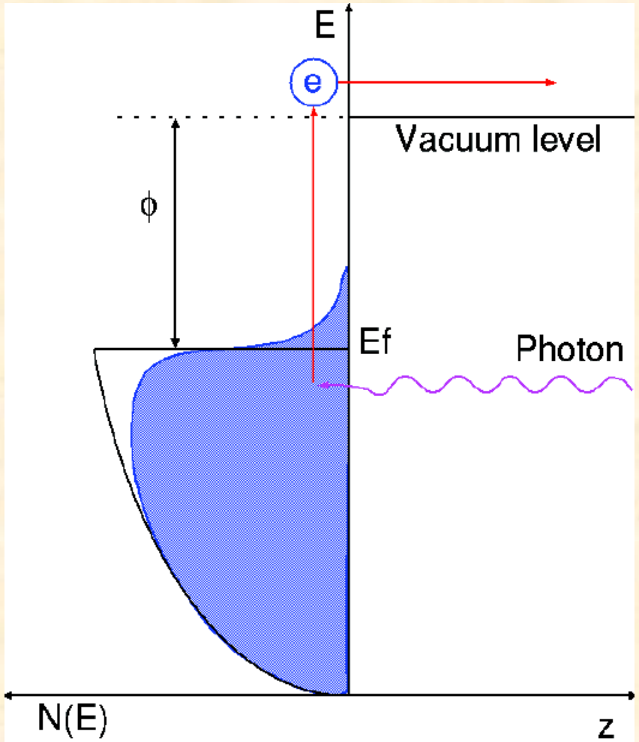
- The lower the work function, the easier it will be for an electron to escape.
  => more electrons will escape at a given temperature
- Gadolinium (b) has the lowest work function and thus it will give a higher current.

Answer 2: (c)

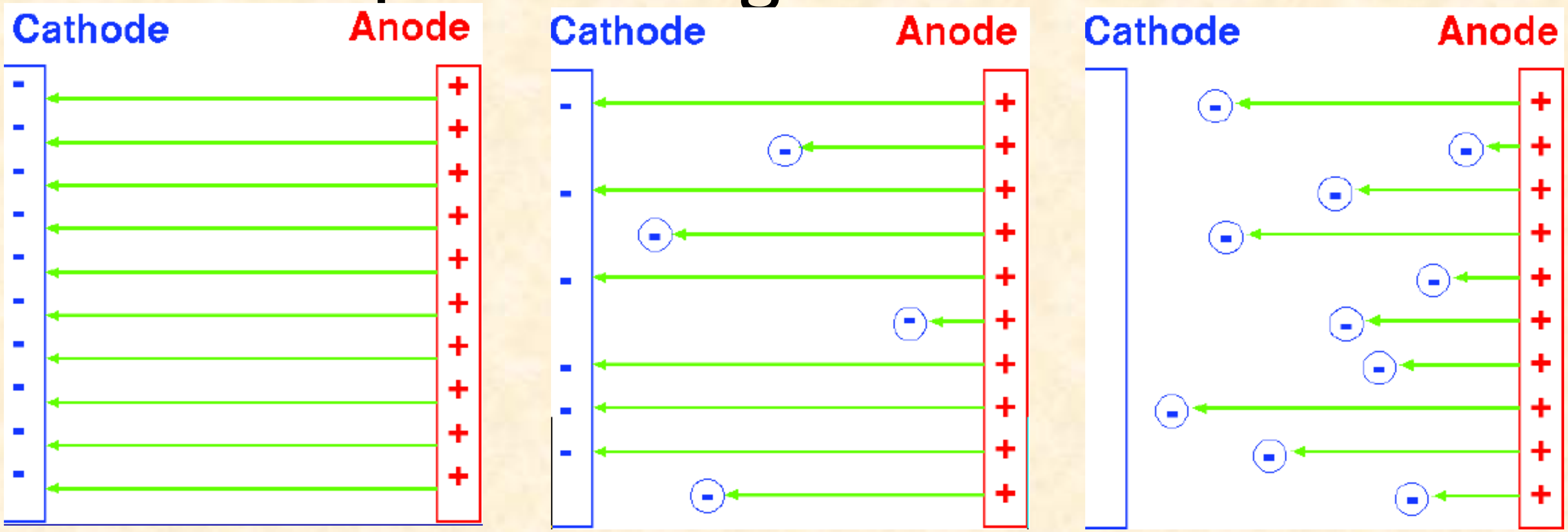
- QE is independent of the laser power: it is the photon energy that matters.
- Remember that

$$E = h\nu = \frac{hc}{\lambda}$$

- The shortest the wavelength, the highest the energy. At 200nm a photon carries ~6 eV, so a 400nm photon carries ~3eV.
- Note: photons with a wavelength of 532nm (2.33eV) or 10 micrometer (~0.1eV) will have less energy than the work function of the photo-cathode (but escape by tunnel effect is possible).



Why we can’t have more particles? Space-charge limitation



- Emitted electrons shield the cathode from the anode => reduced field
- This limits the intensity of the emission.
  Child-Landmuir law (potential V, area S, distance d)

$$J = 2.33 x 10^{-6} S \frac{V^{3/2}}{d^2}$$

PARTICLE ACCELERATION

Special relativity reminder

- In a particle accelerator particles travel at very high speed.
- Special relativity can not be ignored.

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

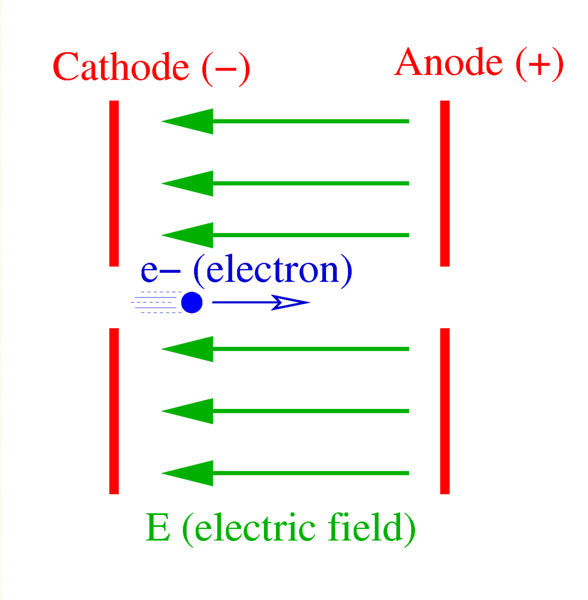
$$E = \gamma m_0 c^2$$

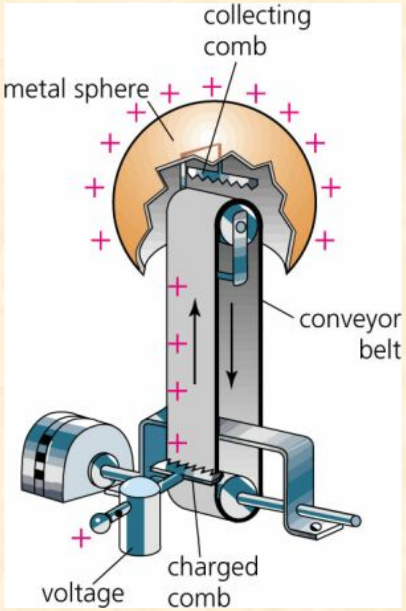
$$\text{Protons: } \gamma = \frac{E}{m_p c^2} \simeq E[GeV]$$

$$\text{Electrons: } \gamma = \frac{E}{m_e c^2} \simeq \frac{E[MeV]}{2}$$

- Typical RF gun (electrons): few MeV => gamma = 5-10
- Typical proton/H- source: hundred kV => gamma less than 0.001!
- Electrons are very quickly relativistic, protons are not!

- Typical synchrotron light source: 3 GeV => gamma = 6000
- LEP energy 100 GeV/beam => gamma = 100 000.
- LHC Energy (so far) 3.5 TeV/beam => gamma = 3500.
- Relativistic phenomena are much more important in electron accelerators than in proton accelerators.



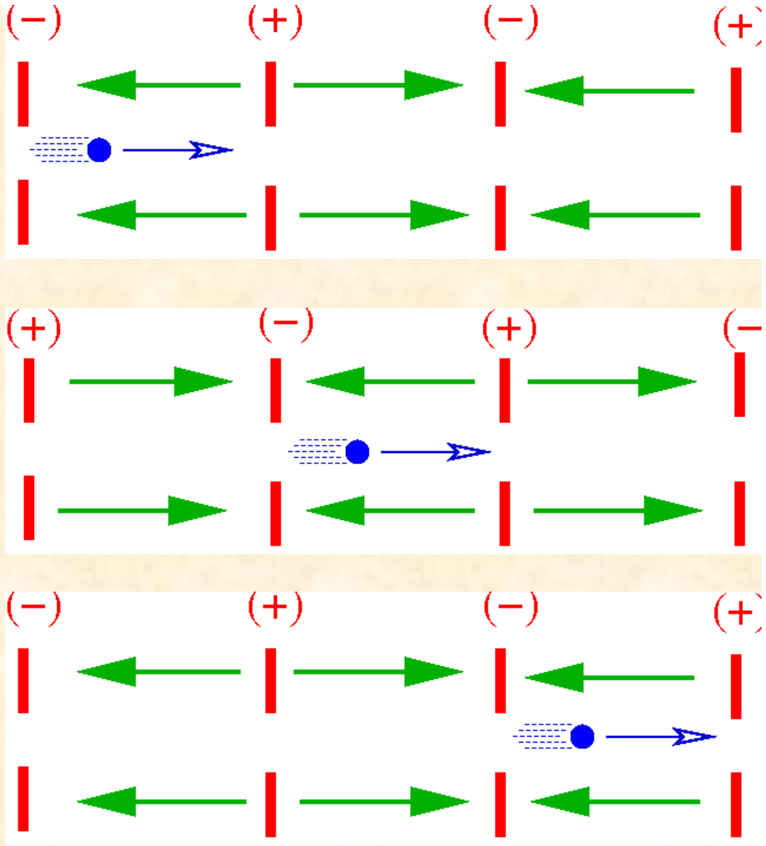


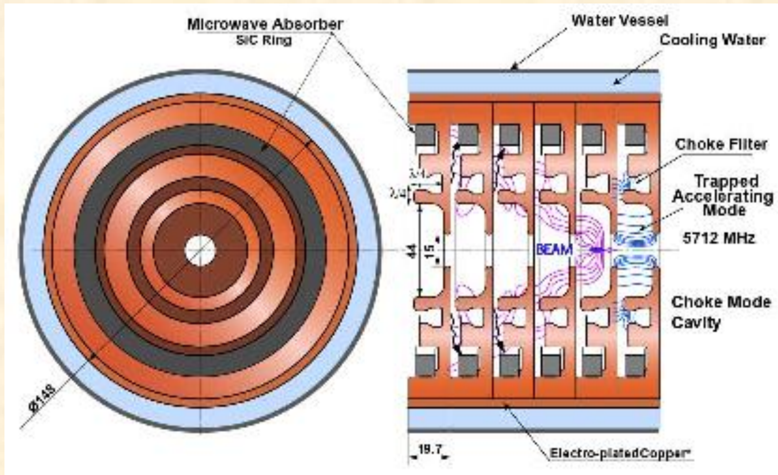
Electrostatic acceleration

- Charged particles can be accelerated in an electrostatic field.
- This works up to a few MV but we have seen yesterday that intense electric fields can be dangerous.
- To reach more than a few MeV, alternating current accelerators must be used.

Particle acceleration

- Particles can be accelerated in a static electric field, however such fields are limited to a few megavolts.
- To go beyond these limits it is necessary to use cavities in which the fields is alternatively accelerating and decelerating. Radio-frequency (RF) cavities use such AC field to accelerate particles to very high energies.
- In a RF cavity the particles “surf” on an electromagnetic wave that travels in the cavity.

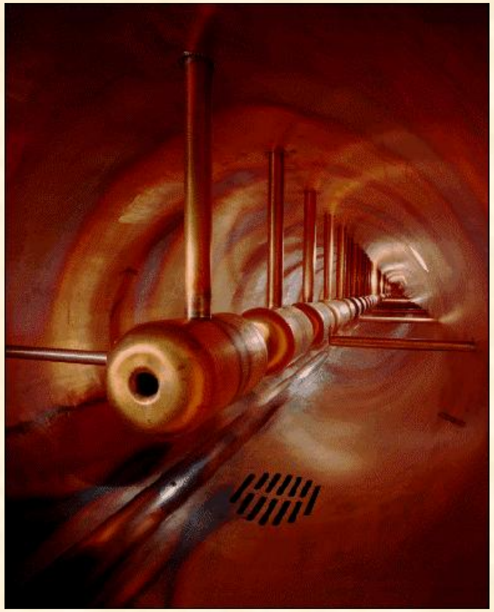




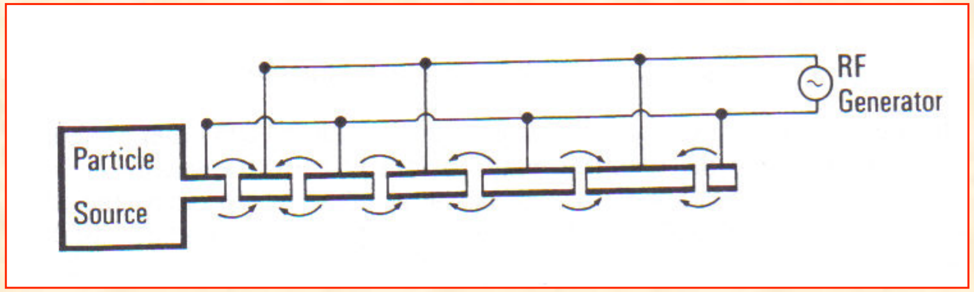
(source: Spring-8, Japan)

RF accelerators (2)

- The first stages of an AC accelerator are quite complicated because the speed of the particles keeps changing and thus the spacing between cavities is changing.
- Once the particles reach the speed of light, the cavities can be evenly spaced.



First stage of a proton RF accelerator



RF accelerators (3)

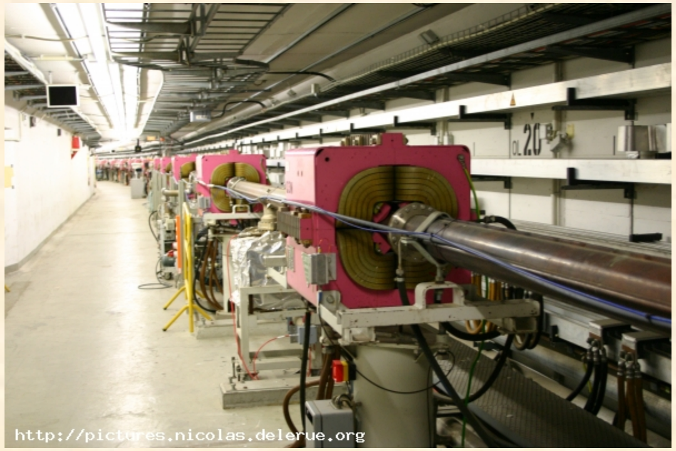
- Because after each cavity the particles return to ground potential there is no theoretical limit on the length of a RF accelerator.
- String of accelerating cavities are usually called “Linac” (Linear Accelerator).
- Linacs are mostly limited by their length: the ILC will accelerate electrons up to 1 TeV, each linac will be ~20km long!

Artist view of the ILC (source: KEK)

PARTICLE CONTROL

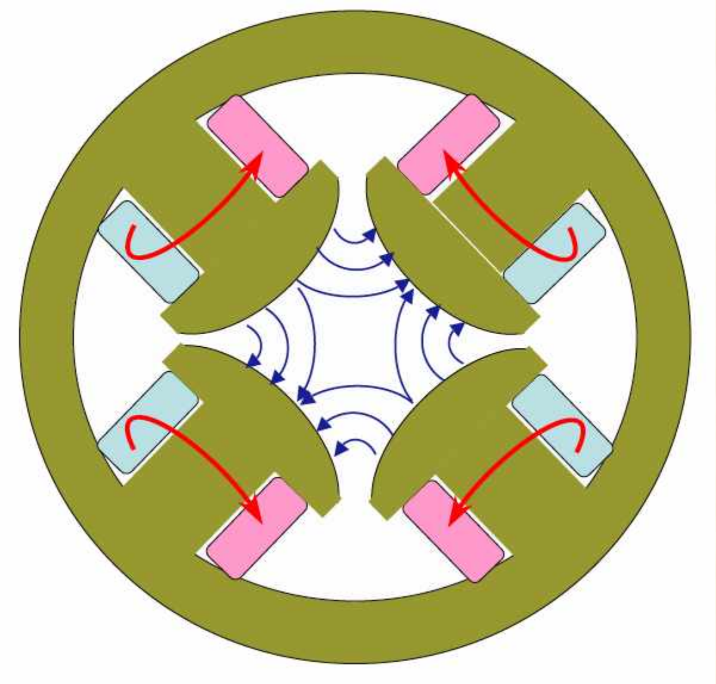
How to control where the particles go?

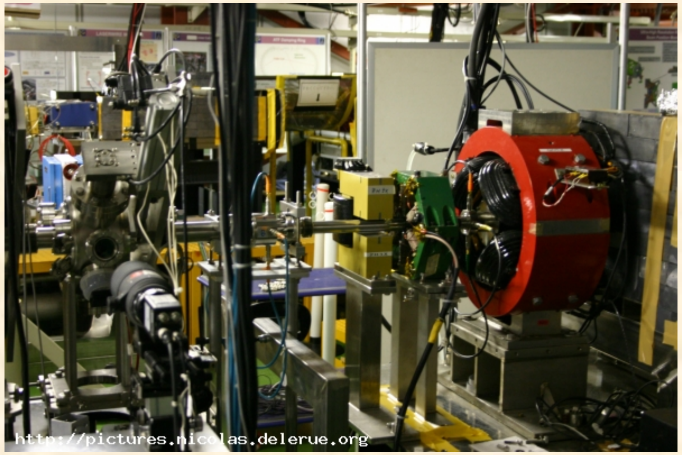
- Electric and magnetic fields can deflect charged particles.
- In an electric field the particles get accelerated.
- In magnetic field the direction of the particles is changed but not their energy.
  => it is preferable to use magnetic field (usually electromagnets) to control a beam.
- Magnets are also more efficient.



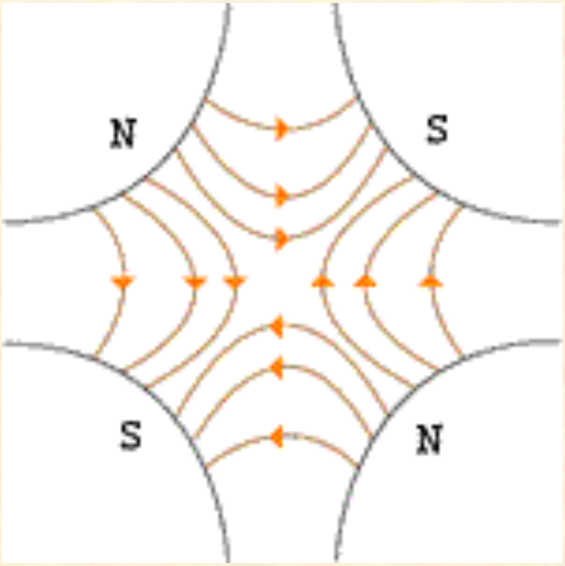
Beam focussing

- A regular magnet (dipole) will create a field that will bend the beam in one direction.
- To change the size of the beam a different type of magnets called quadrupoles need to be used.
- Quadrupoles create intense fields for off-axis particles but do not disturb particles on the axis.

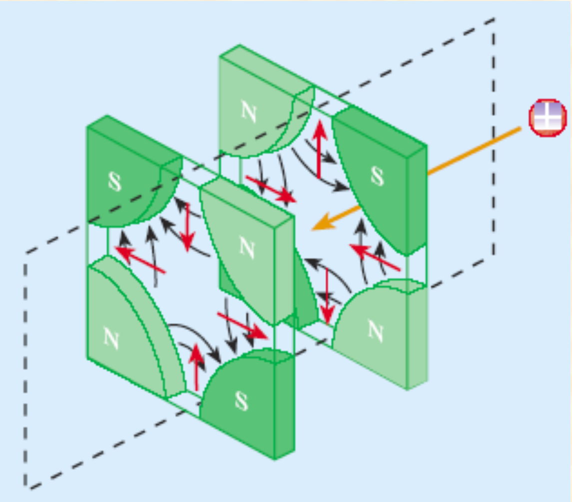


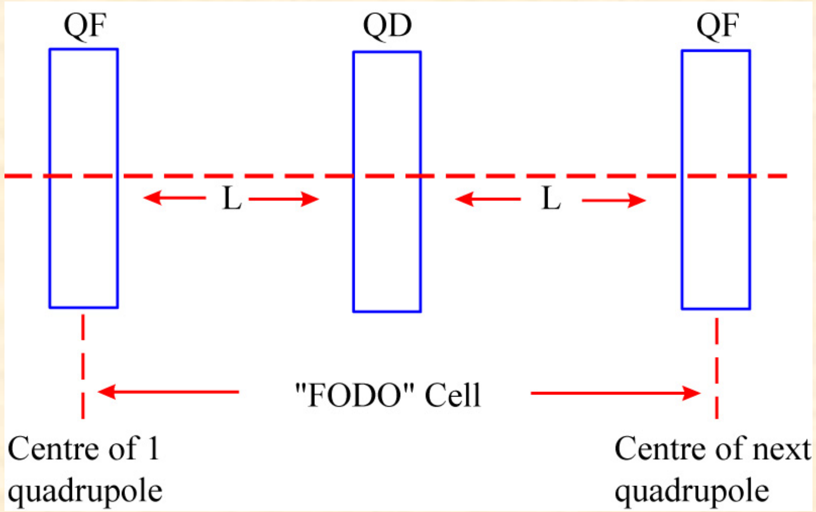


FODO cell



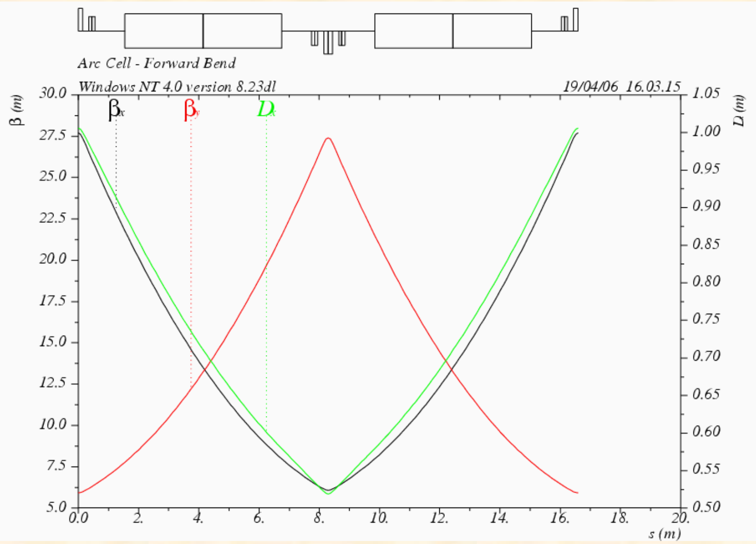
- A quadrupole will focus the beam in one plane but defocus it in the other plane.
- To have a net focussing effect, 2 quadrupoles are used, one focussing in one plane and the other one focussing in the other plane.

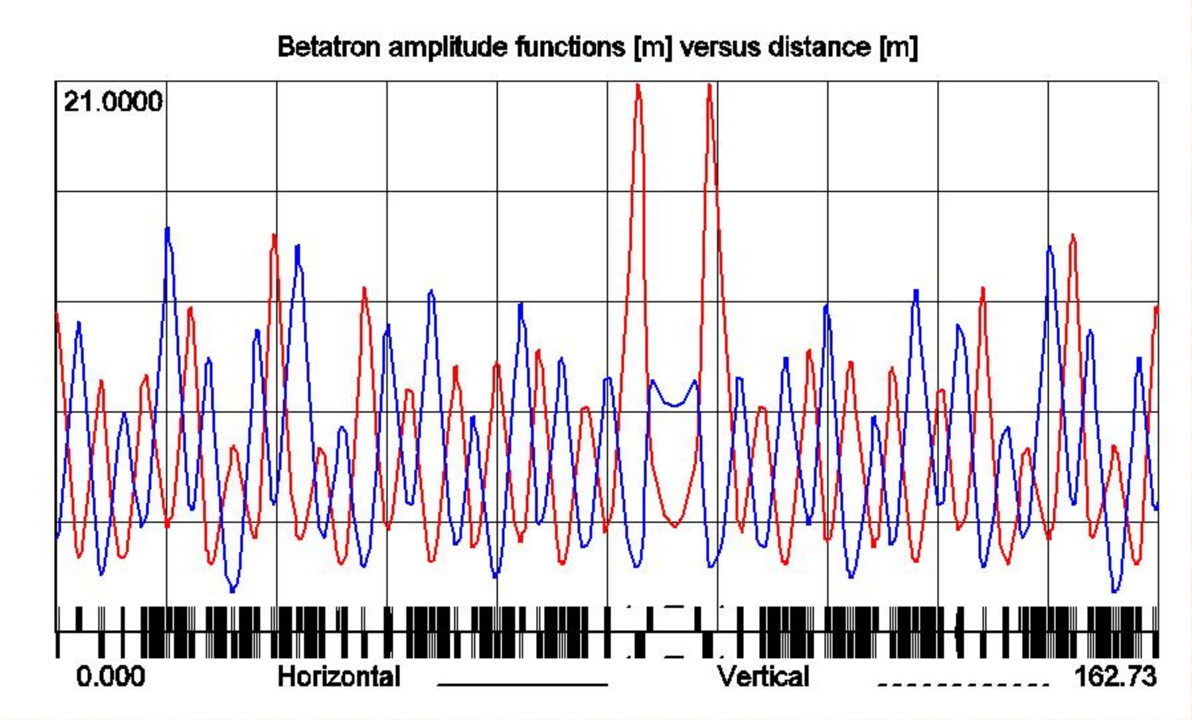


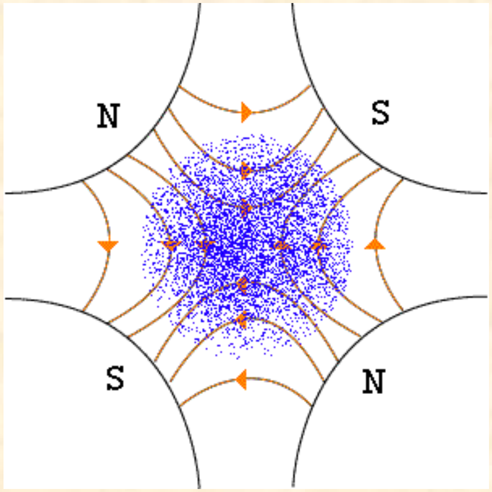


Accelerator lattice

- In an accelerator there is a large number of quadrupoles to keep the beam size under control.
- This is called the lattice of the accelerator.
- The magnet strength are characterised by a "beta" function.







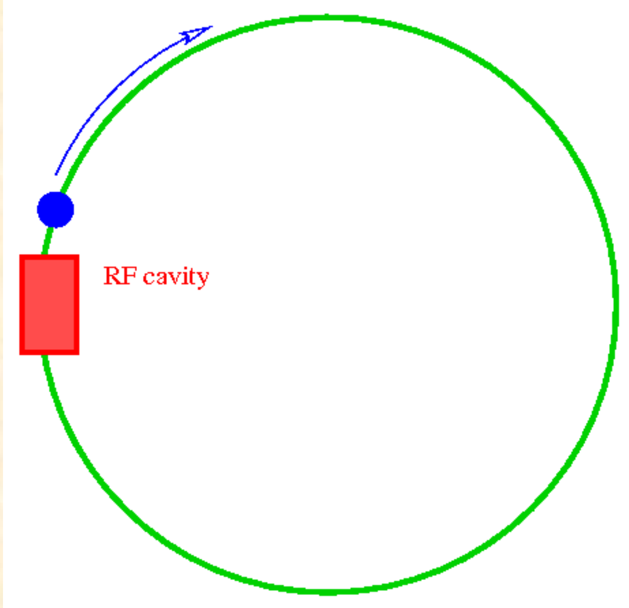
Synchrotrons

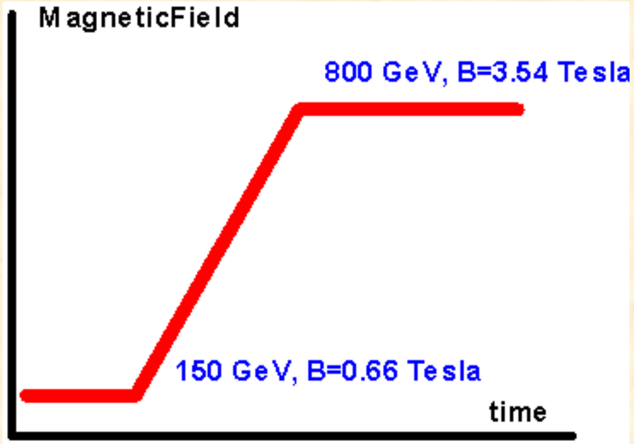
Dipole magnets are then used to make the particles follow a circular orbit.

This can be used instead of having a large number of cavities to accelerate the particles, by using a single cavity in which the particles pass several times.

As the particles gain energy the radius of curvature of their orbit in a constant field increases

=> The field of the dipoles has to be increased as the particles gain energy to keep a constant orbit.





Magnetic rigidity

- The bending power of a magnet depends on the beam energy.
- It is often useful to use the “magnetic rigidity” of a beam.
- One should note that rings often have straight section. So the magnetic radius of an accelerator is smaller than its geometrical radius.
- The LHC has a magnetic radius of 2804m.

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

$$B\rho = \frac{p}{q}$$

$$B[T]\rho[m] = 3.34p[GeV/c]$$

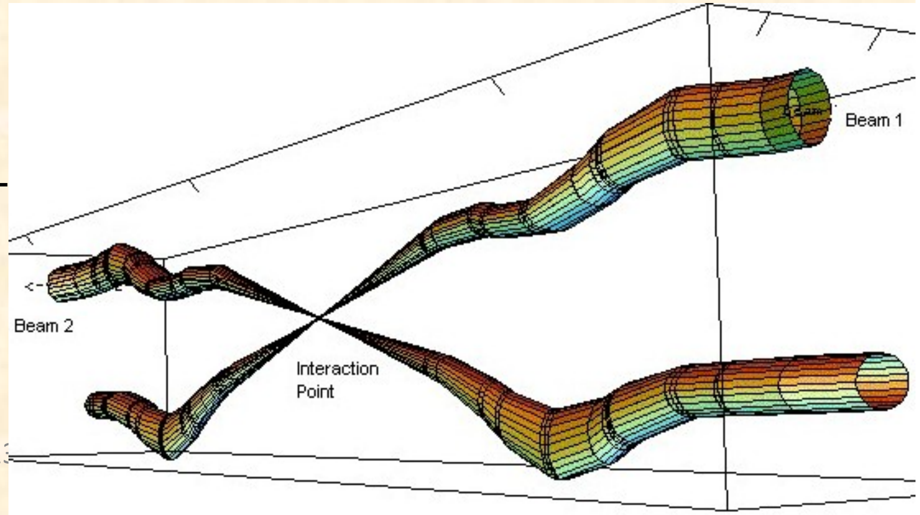
$$B[T] = \frac{3.34 * 4000[GeV/c]}{2804[m]} = 4.8[T]$$

BEAM DYNAMICS

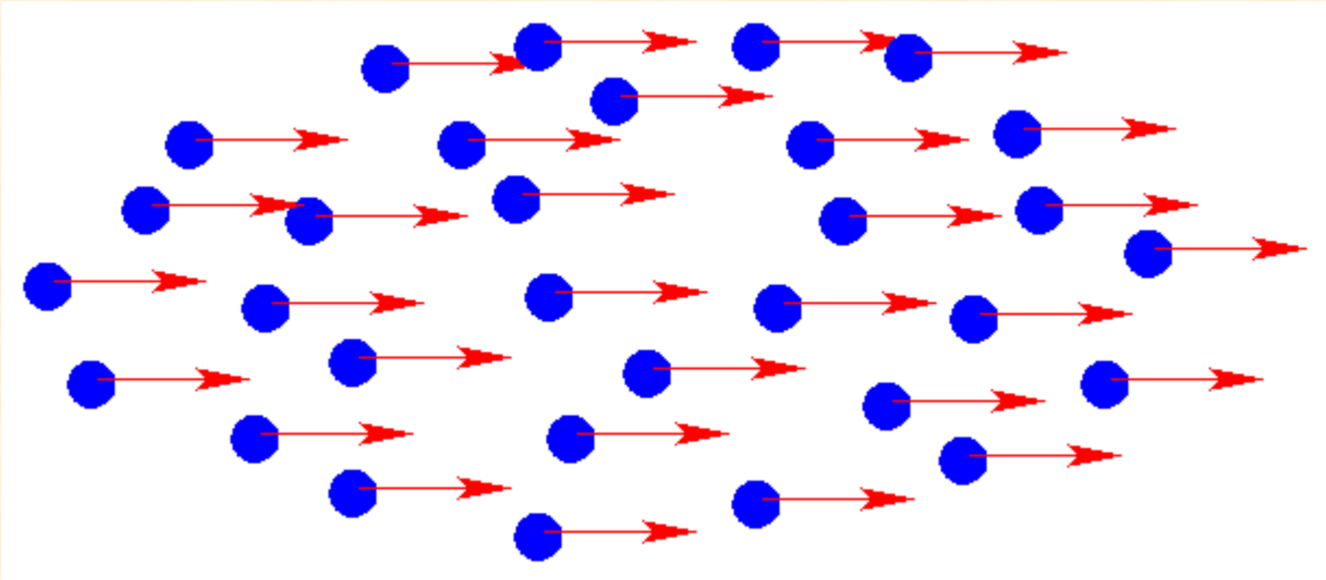
Luminosity

- The luminosity of a collider gives a measure of the number of collisions delivered.
- It is proportional to the collisions frequency and to the bunch charges.
- It is inversely proportional to the beam size.
- However because the beam size at the interaction point can not be measured, it is often written as a function of two other variables: the “emittance” (dynamic properties of the beam) and the beta function (magnetic properties of the beam).

$$\mathcal{L} = \frac{f N_1 N_2}{4\sigma_x \sigma_y} = \frac{f N_1 N_2}{4\pi \epsilon_x \beta_x^* \epsilon_y \beta_y^*}$$



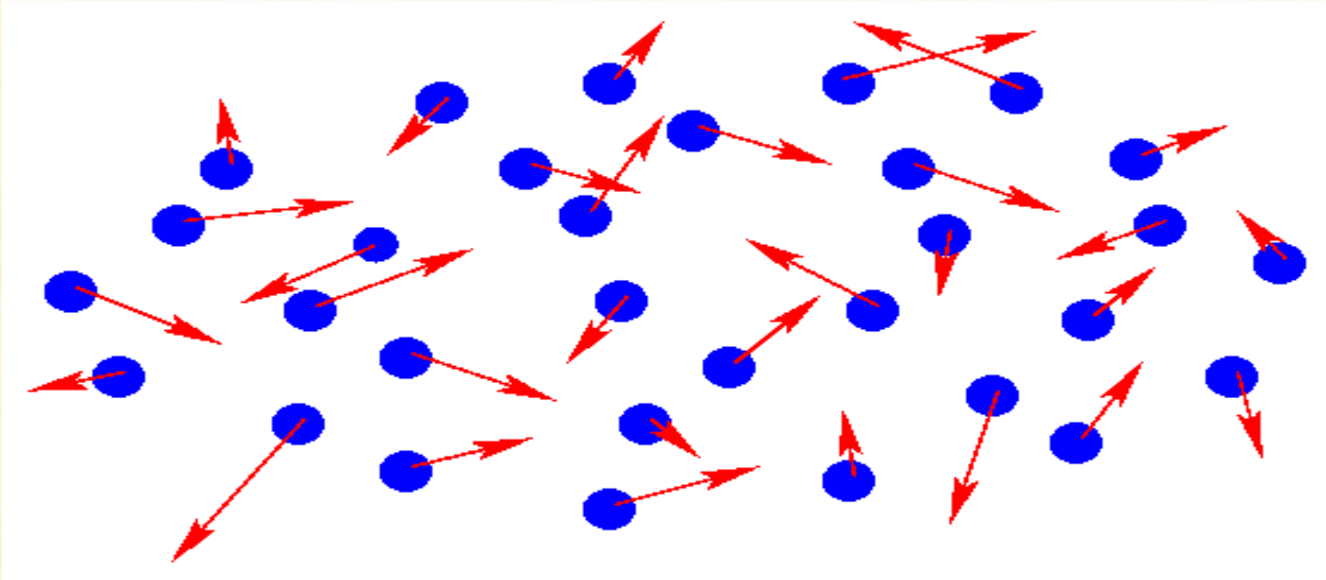
Let's look at a particle bunch



An observer in the laboratory frame looking at a particle bunch will only see particles travelling at the speed of light, apparently all in the same direction.

It is very different if one looks in the bunch's centre of mass frame...

Let's look at a particle bunch



In the centre of mass of the bunch, the particles do not look so well organised...

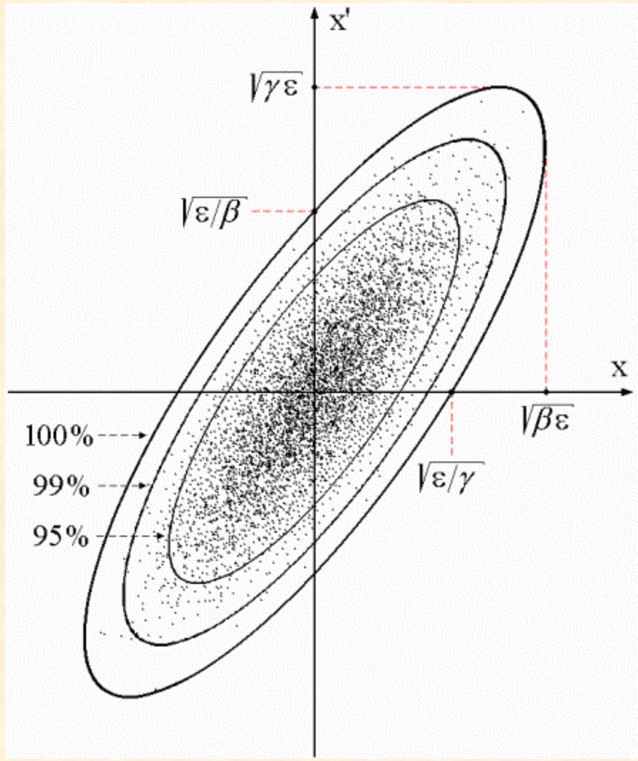
This should remind you other statistical systems that you have already studied: Gases!

Perfect gas law

- You have studied earlier that a perfect gas obeys the law: PV=nRT
- V is the volume term (V=xyz)
- P is a dynamic term: P, the pressure is proportional to the amount of scattering experienced by atoms as they travel in the volume. It is proportional to the momentum of the gas atoms (P~x'y'z').
- Hence it is possible to write that for gas atoms the product of their position by their momentum is expressed by their temperature *(times a constant).*
- We have seen that in the CoM particles look like a perfect gas. The product of their position by their momentum is called the "emittance" of the beam.

Emittance

- We have defined the emittance as the volume occupied by the beam in the trace space.
- Liouville's theorem tells us that such volume must be constant.
- Hence the emittance of a beam is constant (unless external forces are applied).



- The total volume occupied by the bunch in trace-space is usually dominated by a few far-outlying particles.
- Instead of giving the volume occupied by all the particles, it is common to give the volume occupied by 90% or 60% of the particles or to give the RMS emittance.
- The fraction of particles included in the emittance is usually quoted.

$\in_{90}$ $\in_{RMS}$

Quizz

1) Is the emittance of a particle beam an intensive or an extensive physical property?

- a) Intensive
- b) Extensive

2) In which units should the transverse emittance in 1 dimension (x,x') be expressed?

- a) Square metres
- b) Barns
- c) Metre x radians
- d) Kelvin

Answer: (1b)

- Emittance is the product of the beam size by the beam divergence.
- Both are extensive quantities
- The emittance of a fraction of a beam will be smaller than the emittance of the full beam.

$$\in_{90} > \in_{60}$$

- This property is used in particle accelerators: the emittance of a beam can be improved by trimming it.

Answer: (2c)

- The size of the beam is expressed in (milli)metres.
- The divergence of the beam can be expressed either in (milli) radians or in eV.
- Depending on conventions a factor Pi may be added.
- A typical emittance for an electron linac with a thermionic gun is mm.mrad.
- A synchrotron can go below nm.mrad.
- Do not forget that 1 mm.mrad = 1um.rad!

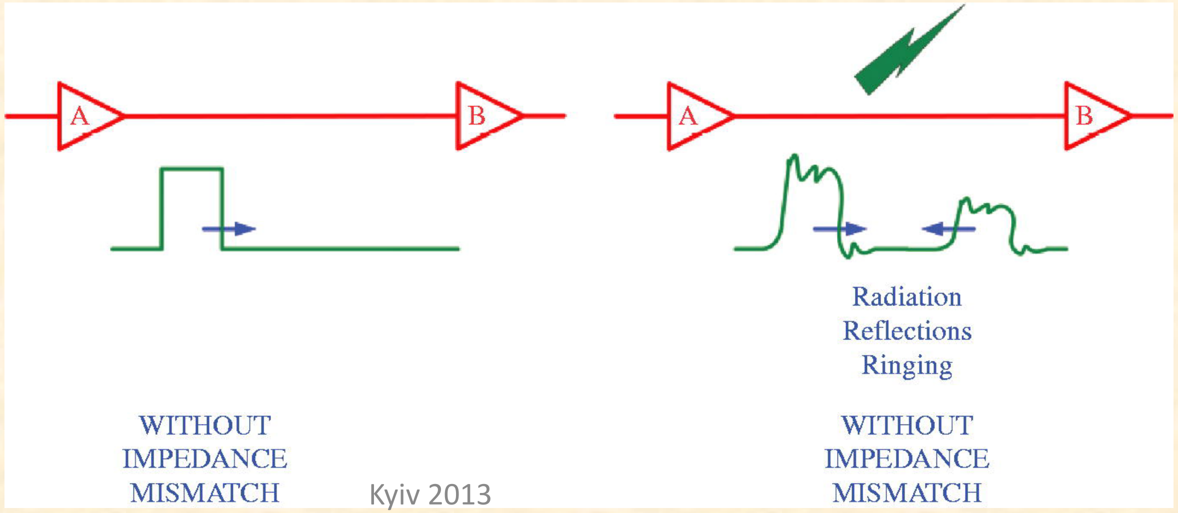
Wake field issues

- Electrons produce an electromagnetic wave behind them.
- This can be compared the to wake of a boat and is called wake field.
- Imagine what would happen if there was a second surfer on the picture below...
- How good is the wake for the walls of the canal?
  It is not good for the beam pipe either!

Source: Reuters

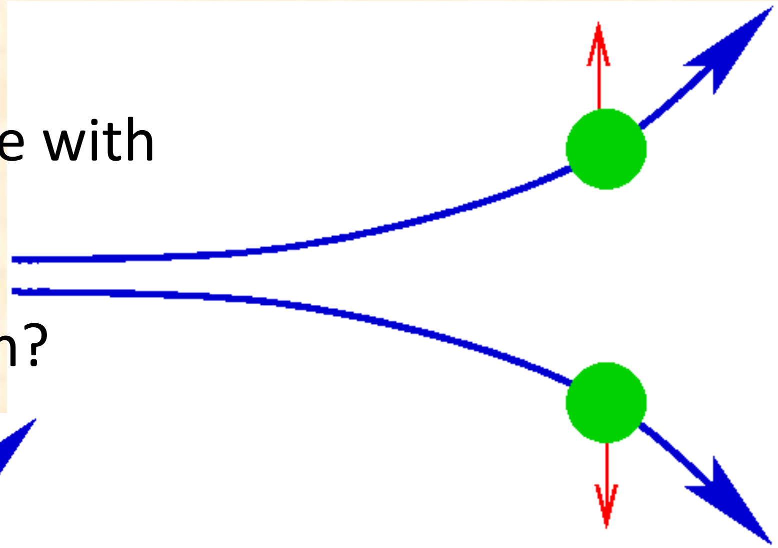
Impedance matching

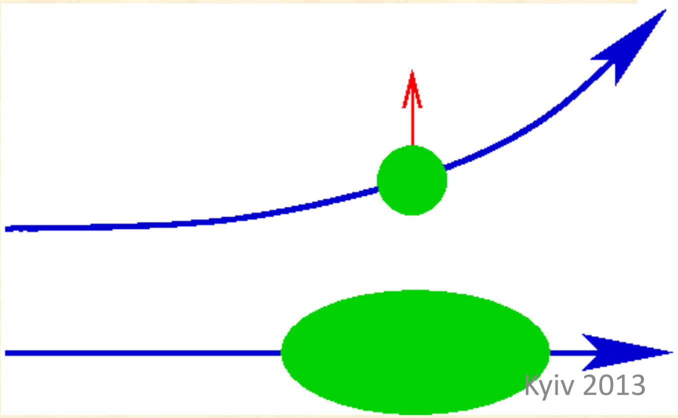
- In a electronic circuit an impedance mismatch will result in a reduced transmission at the interface.
- The same is true in an accelerator: an impedance mismatch is likely to induce a reflective wave at the interface.
- This will induce a loss of power and an emittance increase.
- In a synchrotron the impedance of all beam pipe elements is carefully controlled.
- This is less important in a transfer line where the beam passes only once.



Space-charge effect

- Now let's consider two particles with similar charges travelling in the same direction.
- Due to their charge these particles will push each other away (Coulomb's law).
- What is the intensity of the force with which they repel each other?
- What is the effect of a full bunch?

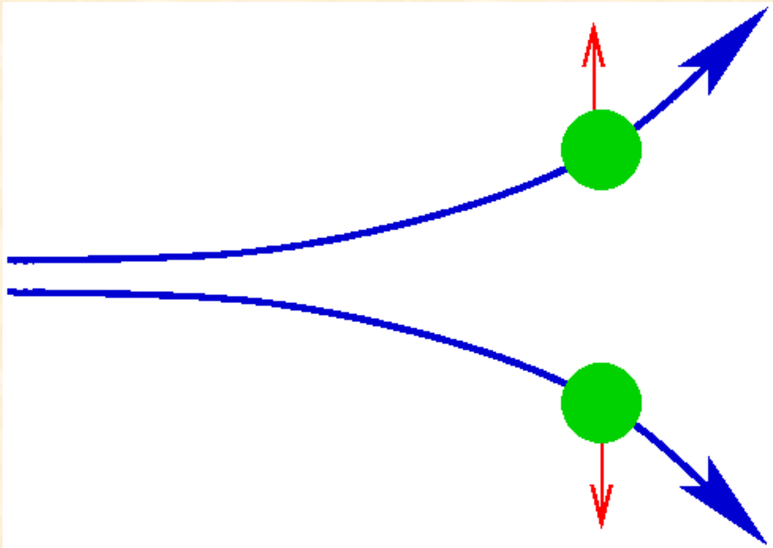


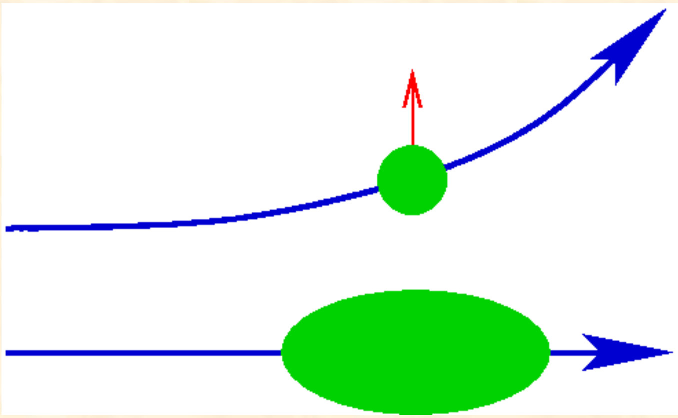


Coulomb force between two electrons

$$f = \frac{1}{4\pi \in_0} \frac{q_1 q_2}{d^2}$$

- Assume d=1micrometre.
- $f = 2\ 10^{-16}$N
- This may look small but an electron is not very heavy
- $f/me = 2.5\ 10^{14}$N/kg
- This force is very intense on the scale of the electrons.
- Typical charge in a bunch: ~1nC = $1.6\ 10^{10}$ electrons





BEAM DIAGNOSTICS

Could you imagine driver a car without looking at the road?

The same applies for accelerators!

What do **<u>we</u>** want to know

about the beam?

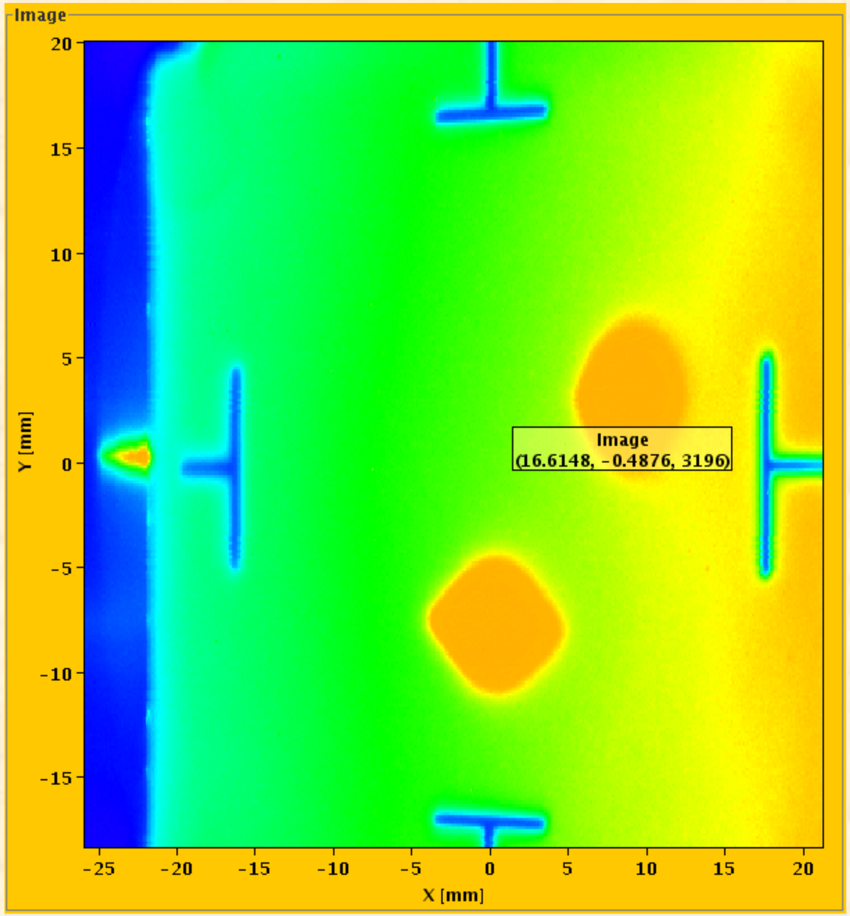
?

Beam properties measurements

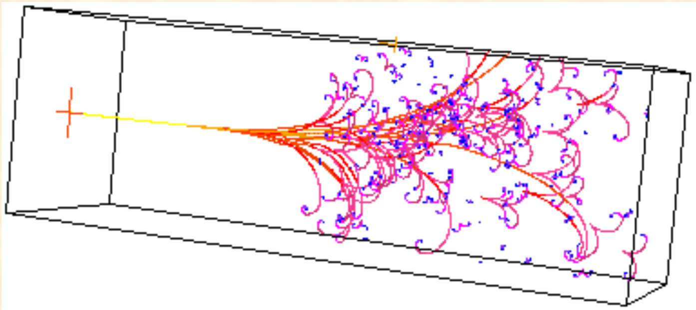
- Almost all accelerators accelerate ***charged particles***
- There are mainly 2 types of beam diagnostics:
  - Diagnostics that use the interaction of the beam with matter (see Maxim's lecture)
  - Diagnostics that use radiations emitted by the beam to measure its properties.
- That's almost all what you need to use to build diagnostics (together with some clever tricks).

What do you want to know about the beam?

- Intensity (charge) (I,Q)
- Position (x,y,z)
- Size/shape (transverse and longitudinal)
- Emittance (transverse and longitudinal)
- Energy
- Particle losses



Faraday cup



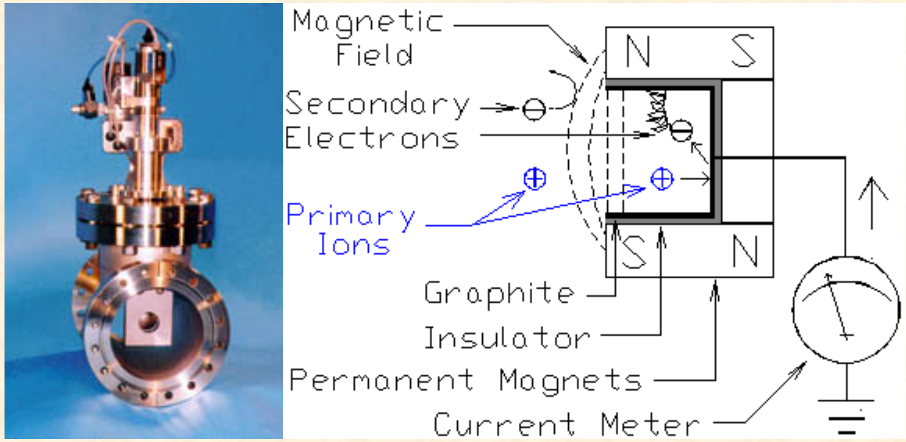


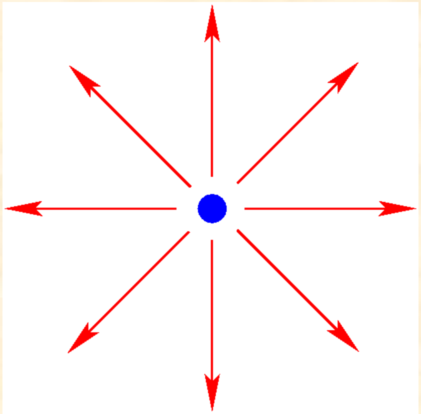
Image source: Pelletron.com

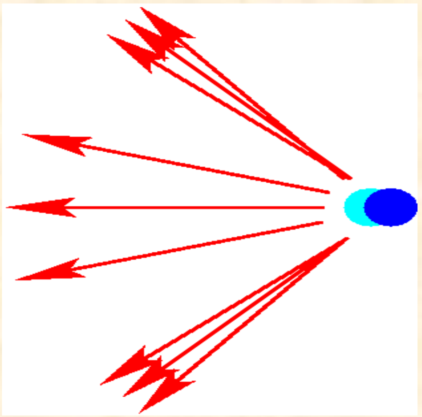
- Let’s send the beam on a piece of copper.
- By inserting an ammeter between the copper and the ground it is possible to measure the total charge of the beam.
- At high energy Faraday cups can be large:
  More than 1m at SOLEIL for a 3 GeV electron beam.

Screen

- If a thin screen is inserted in the path of the particles, they will deposit energy in the screen.
- If this screen contains elements that emit light when energy is deposited then the screen will emit light.
- Example of such elements; Phosphorus, Gadolinium, Cesium,...

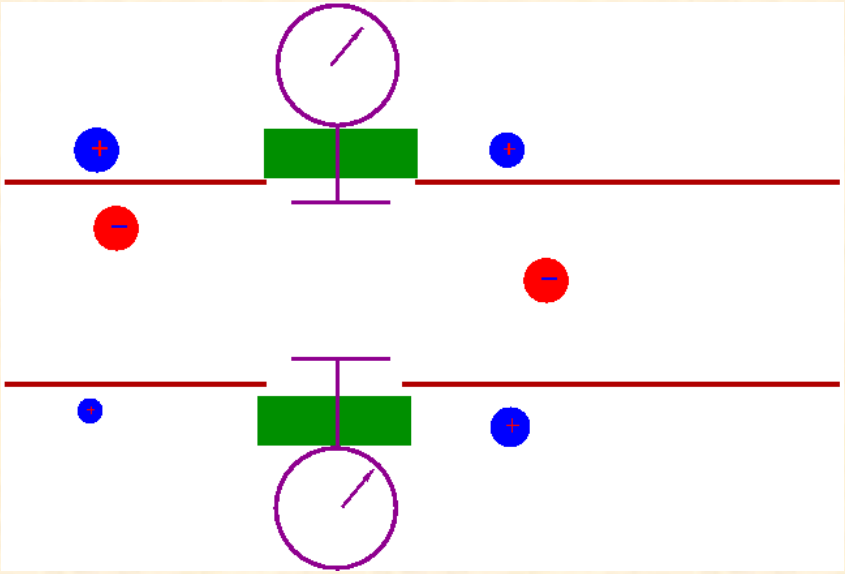
Particles radiation

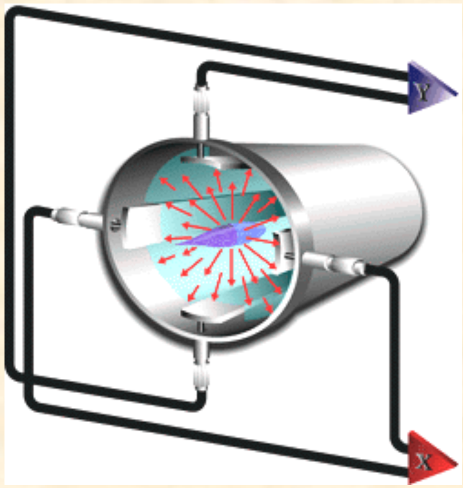




- Any charged particle "radiates"
- These electromagnetic radiations can be detected without disrupting the beam.
- One needs to remember that the beam travels at high speed:
  the radiations will be contained in a 1/gamma cone.

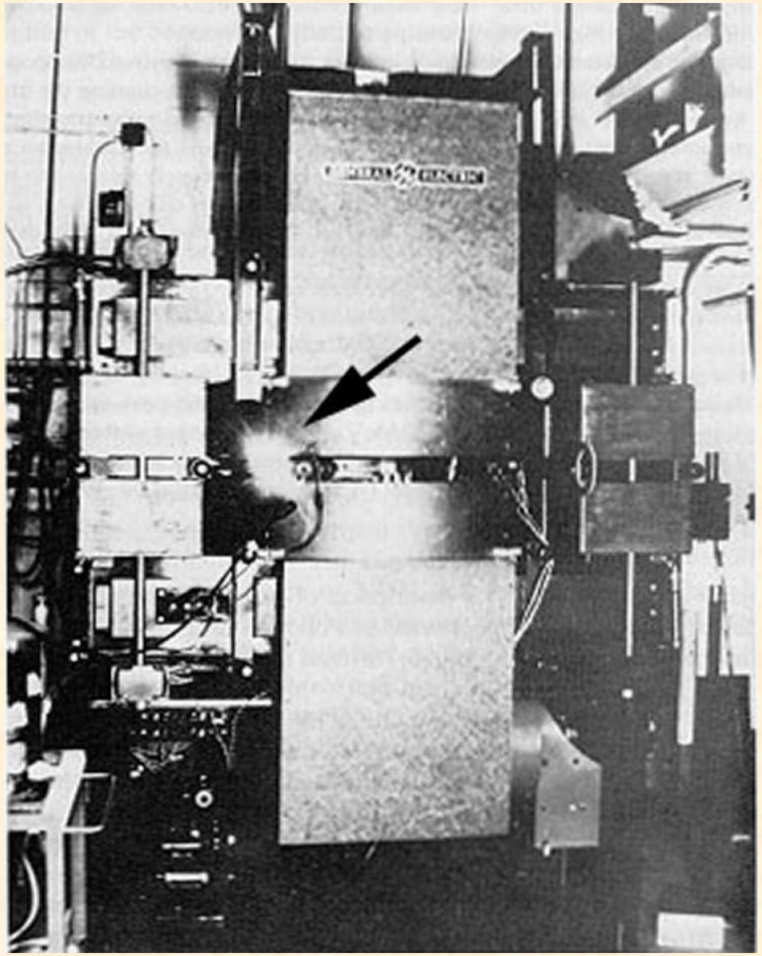
Beam position monitor



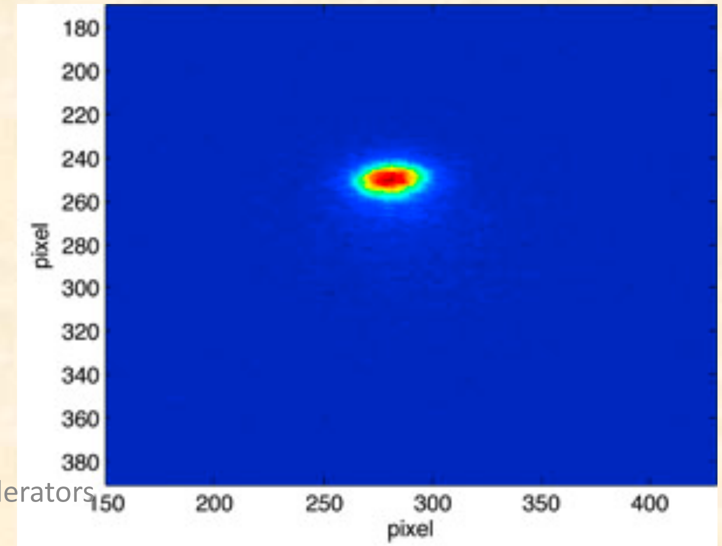


- By inserting two electrodes at opposite locations around the beam pipe, they will be sensitive to the beam position.
- Here the electrodes act as antennas.
- Such device is called a beam position monitor.
- Many flavours of BPM exist.

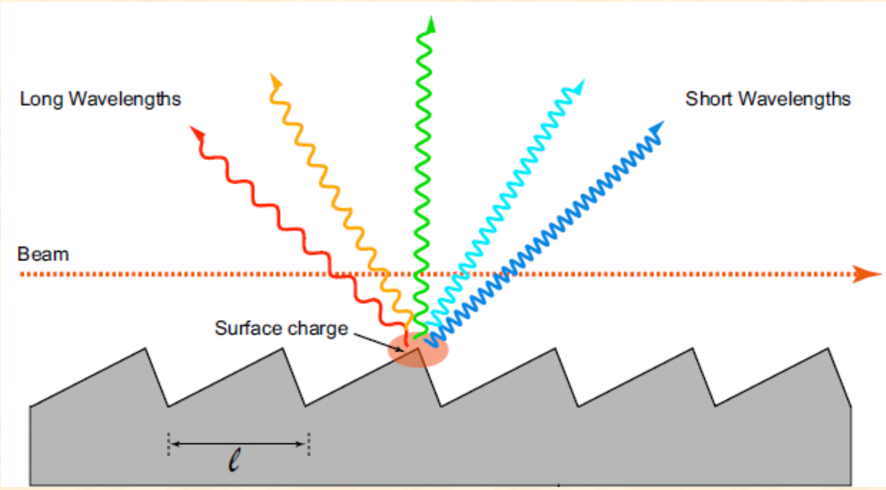
Synchrotron radiation



- Synchrotron radiation carries information about the beam which emitted it.
- It is commonly used to study the beam transverse profile.



Longitudinal profiles



- Longitudinal profiles of short beams are one of the most difficult measurement.
- Several techniques use radiation induced by the beam.
- In the Smith-Purcell method a grating is used.
- The beam interacts coherently with the grating and emits radiation.
- The intensity and wavelength of this radiation depends on the longitudinal profile of the beam.
- Most longitudinal profile measurement techniques actually measure the Fourier transform of the beam
=> reconstruction needed!

$$\left(\frac{dI}{d\Omega d\omega}\right)_{N_e}(\Omega,\omega) = \left(\frac{dI}{d\Omega d\omega}\right)_{sp}(\Omega,\omega)\cdot[N_e + N_e(N_e+1)\,|\,F(\omega)\,|^2]$$

Diagnostics overview

	Interaction with matter	Radiation
Charge	Faraday cup	Beam current monitor
Position	Screen	BPM
Size or shape (transverse)	Screen or wire-scanner	Synchrotron radiation or optical transition radiation
Size or shape (longitudinal)	RF cavity + screen	Radiation detectors (eg: Smith-Purcell)
Energy		Bending magnet
Losses	Scintillator	

Summary

- Protons used in the LHC are extracted by ionising hydrogen.
- Electrons can be produced via the thermionic effect or the photoelectric effect.
- RF cavities are used to accelerate the particles.
- Magnets are used to control the trajectory of the particles.
- The dynamics of the particles in the accelerator is very complicated.
- Bunches too close from each other will damage each other by their wakefields or by electron cloud effect.
- Beam diagnostics allow to see what happens in the accelerator to control and reduce the effects described above and bring the beams to collisions.
- We did not have time to discuss applications of particle accelerators…